THE UNIVERSITY OF QUEENSLAND

Master of Engineering Thesis

Trombe Wall Conditioning for Nepal

Student Name: Philip Daniel EDWARDS

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Supervisor: Associate Professor Kamel Hooman

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UQ Engineering

Faculty of Engineering, Architecture and Information Technology

EXECUTIVE SUMMARY

Climate comfort is often taken for granted. However even in moderate ambient conditions, indoor climates can lack comfort without the use of appropriate resources. Around Nepal the average climate conditions range from -10 to 40°C with relative humilities ranging from 37% to over 80%. This is coupled with limited economic resources and access to grid electricity, which restricts the use of active modern conditioning systems (such as heat pump air-conditioning).

This report explored passive conditioning methods in climates around Nepal to improve climate comfort. These methods include evaporative cooling, use of ground source thermal energy and solar heating. A trombe wall model was then analysed in detail due to a simple design, utilising solar energy to drive convection currents within an air gap. Standards were compared to achievable climate comfort conditions provided by the American Society of Heating, Refrigeration and Air Conditioning Engineers (AHSRAE).

A trombe wall model was solved by considering an iterative solution method of one-dimensional heat transfer and an efficiency of heat removed by convective airflow. Important inputs included the ambient temperature, room thermal resistivity and solar irradiance. The incident solar irradiance has been modelled as varying throughout the day, according a method outlined by ASHRAE and subsequent locational data. The room temperature was modelled over a day by considering room thermal resistances from 0.004K/W to 0.05K/W, and the ambient temperature variation.

Results showed that a wall area of 1.4m x 2.5m can provide 6 hours of thermal comfort with ambient daily temperatures between 5.7 and 15°C in Okhaldhunga, Nepal, given 0.03K/W room thermal resistance. The same comfort condition was achieved for an ambient daily temperature range from -10.1 to 6.9°C in Lhasa, China with a 5m x 2.5m wall, and 0.03K/W room thermal resistance. 6 hours above a minimum ventilation flow rate, as recommended by ASHRAE was also achievable. This was modelled as exhaust flow vented to the outside, with a wall height of 2.5m and lengths between 3.5m and 4.1m depending on location.

ACKNOWLEDGEMENTS

I would like to thank Engineers Without Boarders and Smart Shelter Research for introducing me to this project. I thank Nick Brown for providing invaluable insight into humanitarian engineering and Martijn Schildkamp for knowledge of best practice construction techniques within Nepal, and them both for their ongoing support. I would also like to thank my supervisor Kamel Hooman for guidance throughout the project and the University of Queensland for access to resources.

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1. INTRODUCTION

1.1. PROJECT OVERVIEW AND MOTIVATION

Studies have found that conditions of working environments effect intellectual performance for workers in office spaces (Fisk, 1997), as well children in classroom environments (Bako-Biro, Clements-Croome, Kochhar, Awbi, & Williams, 2012; Mendell & Heath, 2005). However, much of the majority world nations lack electricity and income for common climate conditioning systems. This puts to question how we can best utilise available resources to improve the thermal comfort of working environments in areas such as Nepal and similar regions. This report explores possible solutions to this problem and provides an in-depth analysis of a trombe wall system for typical Nepalese climates.

The project has been initiated with ongoing interest through Smart Shelter Research to address issues of realistic methods of improving climate comfort in Nepal. Other key stakeholders include Engineers Without Boarders, as a project partner sourcing researchers and the University of Queensland. While these stakeholders have interest in the success of this project, there are minimal investments and therefore low risks to each. Primary risk considerations include inaccurate outcomes and poor implementation that could have negative effects on the community. For this reason, a number of recommendations have been made involving further analysis and proof of concept modelling.

A trombe wall can provide either heating or ventilation depending on the location of vents. The model used in this analysis was based on a one-dimensional analysis of heat loss, with useful heat delivered by a convection current up the wall, and heat conducted through the wall thickness. This is used in a time step model of room temperature and ventilation flow, considering heat exchanges between the room and atmosphere.

The potential thermal heating of this technology has been quantified against comfort conditions of low mobility office and school working environments within Nepal. The ventilation provided is compared to ASHRAE Standards for Natural Ventilation (ASHRAE, 2016).

It is recommended to consider additional cultural, social and environmental factors. Environmental factors include climate modelling and potential impacts towards the environment. Cultural factors regard the integration of the system with cultural ideas, especially regarding architectural ergonomics and any other further beliefs and practices of the population.

Social factors are the potential benefits from improved climate comfort conditions. These will determine the effective life-cycle operation of the system.

1.2. DESIGN SCOPE

This design was targeted for typical climatic conditions in Nepal and close regions within Asia. Additionally, a climate comfort level has been determined. This comfort level is combined with climatic data and typical properties of architecture within these areas to give an estimate of conditioning effects.

Two regions of Nepal have been analysed: Nepalgunj and Okhaldhunga. These regions represent a warmer and colder Nepalese climate respectively (Appendix 9.1 & 9.2). They are also distanced from the power network, with Okhaldhunga approximately 50km from the nearest substation (Appendix 9.3), but both have reasonably high population densities of 138 and 210 pp/km2 for Okhaldhunga and Banke Districts (where Nepalgunj lies) respectively (illustrated in Appendix 9.4). Three regions close to Nepal were also considered. These are the cities of Patna and Guwahati in India, and Lhasa in China.

To ensure the system is relevant to use in these areas, both access to appropriate resources and cultural integration must also be considered. Resources include available materials, work on installation, operation, maintenance and decommissioning as well as financial access for external sourcing. While some of these factors have been quantified, literature studies will give an overview of a level of appropriateness, which will need to be validated through direct consultation with the community. Additional analysis of radiant temperature, temperature gradients and air speed is recommended as these have not been considered in the scope of this report.

1.3. PROJECT OBJECTIVES

Project objectives are stated in Table 1. Overall, this report will enable decision-makers to determine whether to incorporate this technology into the construction of buildings to improve thermal comfort.

Table 1, Project objectives and considerations

Scoping Objectives	
1	Quantify both, climatic conditions and climate comfort factors for work and study in Nepal.
2	Analyse a trombe wall design for heating potential in a cold location and ventilation potential in a hot location selected in Nepal.
3	Compare comfort conditions attainable in further regions within Asia.
Additional Considerations	
Aesthetic	Appealing to culture, considering the traditional and new architecture.
Practical	Simple to operate and maintain.

2. LITERATURE

2.1. CLIMATE COMFORT

The relevant literature was used to define a climate comfort and explore appropriate technology. Additionally, the relevance of a trombe wall in heating and ventilation was interpreted into Nepalese contexts through literature and calculation.

Climate comfort depends on a thermal comfort level in which a person feels comfortable. This is also known to benefit intellectual performance. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defines thermal comfort in their standards as "that condition of mind which expresses satisfaction with the thermal environment" (ASHRAE, 2004, pp.4) and identifies six primary factors to consider. These factors are:

1. Metabolic rate
2. Clothing insulation
3. Air temperature
4. Radiant temperature
5. Air speed
6. Humidity

The ASHRAE standards also provide a psychrometric chart to determine a climate comfort level. Figure 1 shows one of these charts given a 1.0 – 1.3 metabolic rate, suggesting low mobility. This is expected to provide 80% occupant acceptability based on 10% dissatisfaction criteria. While this gives an idea of an acceptable climate for initial designs, ASHRAE standards recommend the use of community specific acceptability range. A comprehensive thermal comfort study in Nepal was infeasible for this project, therefore consultation with community is still needed to refine this specific acceptability range.

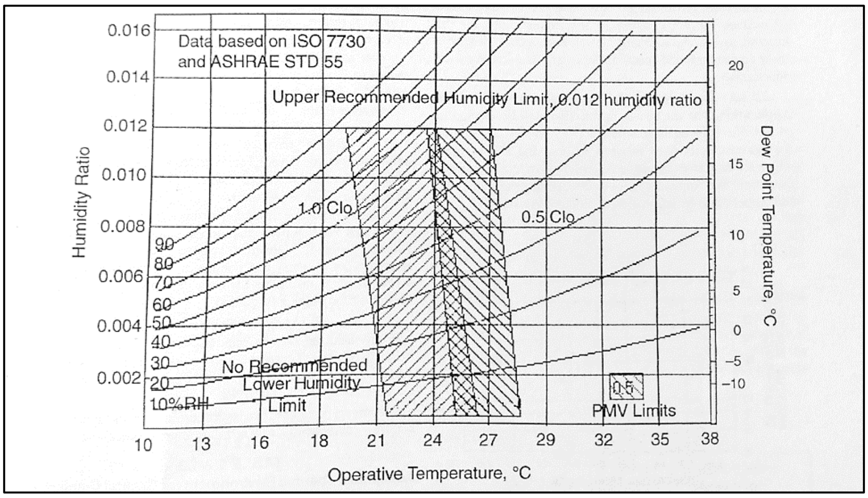


Figure 1 Acceptable range of operative temperature and humidity (ASHRAE, 2004, pp.5)

The ASHRAE standard 62.1 (2016) also specifies minimum ventilation requirements. Given a 36m^2 classroom (age 9 plus), the standard recommends occupancy of 13 people with 87L/s, or 0.087m^3/s air flow ventilation.

2.2. PASSIVE HEATING AND COOLING

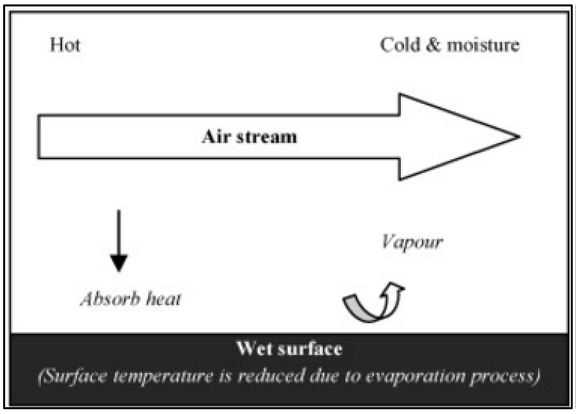
Passive HVAC systems have been explored throughout literature, utilising one or more concepts of buoyancy, insulation, solar heating, natural drafts and evaporation. Table 2 assesses passive heating and cooling systems with specific trail results and a summary of literature comments.

Table 2, Review of passive HVAC concepts

System	Benefits	Limitations
Solar Roof	• A systematic review found passive designs to significantly lower indoor temperature with fan assisted pond reductions up to 7°C (Sharifi & Yamagata, 2015) • Ability to reduce heating loads • Minimal complexity in design needed	• Roof ponds can require large additional infrastructure • Can be limited passive heating potential
Ground Sources	• Often consistent underground temperature and therefore, performance • Study in Malaysia (as a hot and humid climate) delivered 6.4°C cooler air through underground pipes (Sanusi, Shao, & Ibrahim, 2013)	• Require fans to drive air • May not meet cooling demands • Not useful for cooler conditions or hot water • Difficult to obtain underground data
Evaporative Cooling (EC) (Figure 2 & 3)	• Temperature drop of 7.6°C were achieved in Brazil across an evaporative pad (Camargo, Ebinuma, & Silveira, 2005) • Simple process • Potential for utilising exhaust air through desiccant process	• For Direct EC, wet bulb temperature limits the cooling potential • Need for constant water supply

Table 2, Continued

System	Benefits	Limitations
Trombe wall or solar chimney (Figure 4 & 5)	• Effective design can utilise passive operation (Bajc, Todorović, & Svorcan, 2015) • Minimal inputs and maintenance • Adjustable dampers • Addition of external vents (solar chimney) creates ventilation potential • Ability to retrofit	• Requires damper adjustments depending on conditions • Orientation dependent design



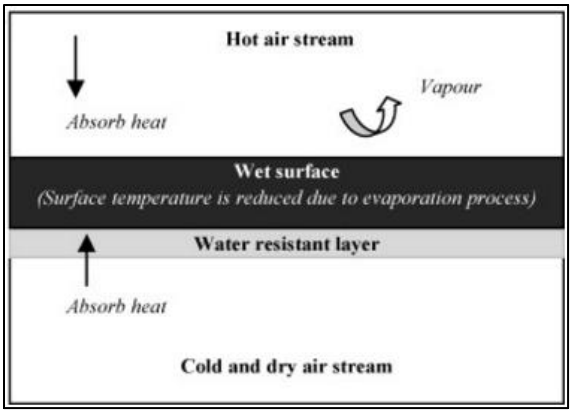
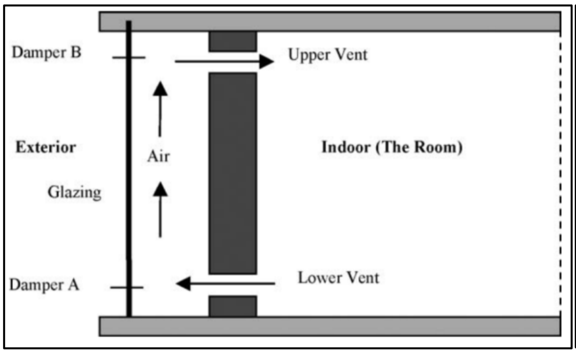


Figure 2 (left), showing direct evaporative cooling and Figure 3 (right), showing indirect evaporative cooling (Chan, Riffat, & Zhu, 2010)



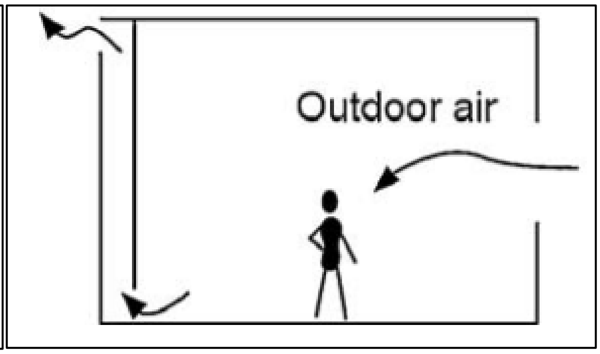


Figure 4, Trombe wall for passive heating & Figure 5 (right), solar chimney for ventilation (Chan et al., 2010)

An article by McFarland & Balcomb shows a comprehensive number of simulations based on varying design parameters of a trombe wall (1979). Despite the age of work, their findings provide a sensitivity and the validation of parameters used. A model based from first principles however, allows more freedom to change parameters and is presented by Tarazi (1991). Tarazi gives a number of numerical outputs, and importantly the heat delivered, as shown in Equation 1. Although this analysis has been refined further in this report, there is still limited evidence to support the validity of this model and therefore, it is recommended to validate model outputs. It is also important to consider the range of inputs valid for this model.

$$Q = A_c F_r \left(c_t w_a I - U_{tot}(T_{in} - T_a) \right) \tag{1}$$

Where:

Q	is the heat delivered by the vents	c_t	is the cover transmissivity
F_r	is the heat removal factor	I	is the radiation intensity
U_{tot}	is the overall teat loss coefficient	T_a	is the ambient temperature
A_c	is the collector area	w_a	is the wall absorptivity
T_{in}	is the inlet temperature		

Air extracted from a building will have a heat transfer effect according to the latent heat removed, given in Equation 2 (ASHRAE, 2013).

$$q_s = Q\rho c_p \Delta T \tag{2}$$

Where:

q_s	is the sensible head load, W	Q	is the airflow rate, m^3/s
ρ	is the air density, kg/m^3	c_p	is the specific heat of air, J/(kg•K)
Δ	is the temperature difference between indoors and outdoors, K		

To select an appropriate passive HVAC system, Nguyen and Reiter (2014) suggest an approach based on the ASHRAE standards (Figure 6). This approach is based on similar comfort conditions and limits of a passive solar heating, direct EC and natural ventilation. Conventional HVAC systems are recommended outside these limits. The approach, is of course limited by assumptions of building envelope, building use and daily radiation.

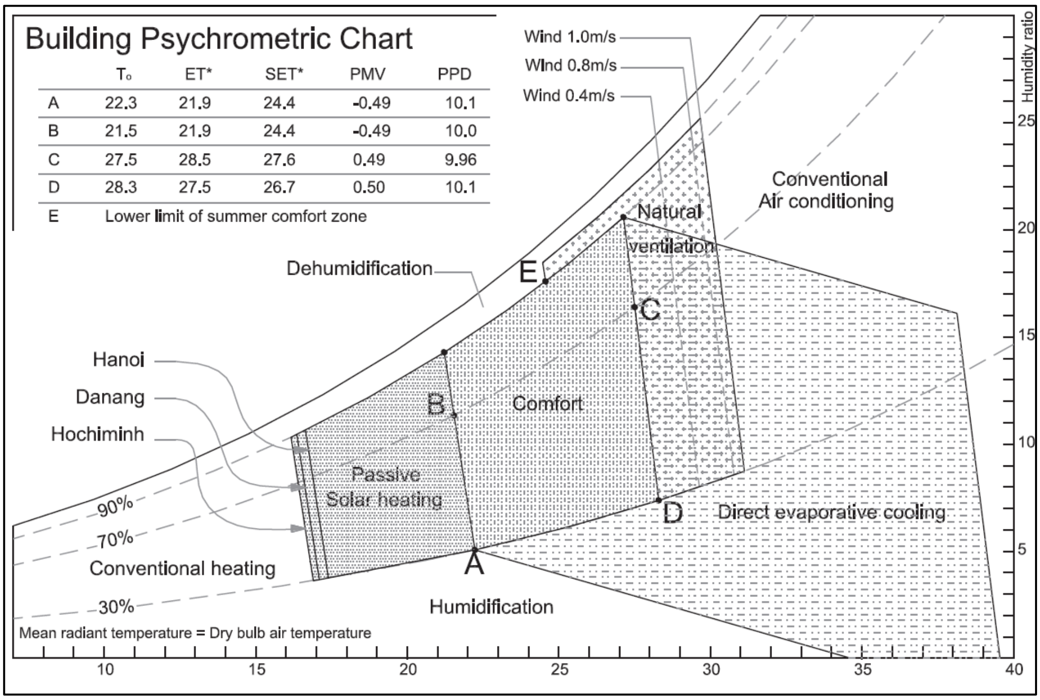


Figure 6, Psychrometric climate comfort zone with temperature given in °C (Nguyen and Reiter, 2014, pp.759)

One method to predict available solar irradiance is found in the ASHRAE Handbook: Fundamentals (ASHRAE, 2013). The handbook relates the incident radiation in three

components of direct, beam and reflection (Equation 27), depending on the orientation, day, time and location-specific variables (depicted in Figure 17).

2.3. NEPALESE CLIMATE

The geography of Nepal creates a range of differing climate conditions across the country. This can be characterised in 5 physiographic regions (shown in Figure 7) ranging from "maximum temperature[s being] more than 40°C in Tarai Plains and extreme minimum temperature less than -20°C in mountain tops" (Department of Hydrology and Meteorology, 2015). This diversity of climates needs to be considered, as it will affect the performance of the passive HVAC systems, and therefore determine their appropriateness.

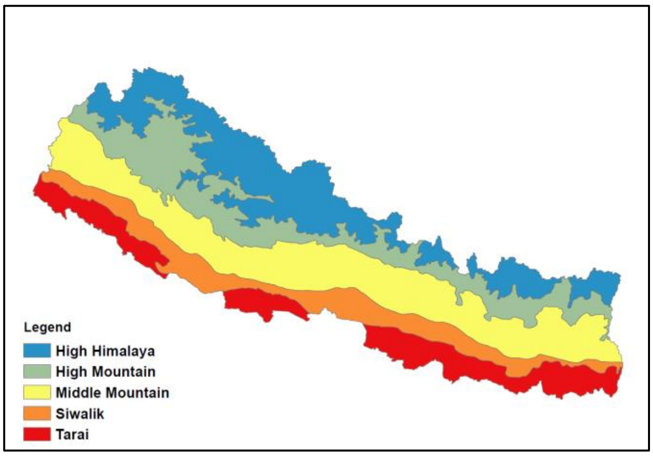


Figure 7 Physiographic regions of Nepal (DMH Nepal Department of Hydrology and Meteorology, 2015)

The city of Nepalgunj and the Okhaldhunga district were selected as hot and cold climate regions within Nepal respectively. Table 3 shows a summary of the hottest and coldest months for these two locations. Nepalgunj in May has the hottest maximum temperature but a hotter average temperature in June. To determine the month with the highest expected cooling load, this data was fitted into a temperature profile suggested in ASHRAE (2013) and shown in Appendix 9.5. The cooling degree hours were then determined between 9am and 8pm by taking the difference in outdoor temperature and desired temperature (of 25°C). This was 114 and 111 (°C·h) for May and June respectively suggesting that cooling in May will be greater.

Table 3, Nepalese annual meteorology summary

	Temperature (°C)			Humidity (%)	Precipitation (mm)	Average Wind Speed (m/s)
	Max	Min	Mean			
Nepalgunj (28.07°N, 81.62°E)						
January	20.9	9	14.9	44	22.8	3.4
May	37.4	24.6	31	56.3	71.4	3.9
June	36.5	26.4	31.5	72.4	199.4	3.6
Okhaldhunga (27.32°N, 86.50°E)						
January	15	5.7	10.3	47.7*	11.7	4.3
May	24.6	15.5	20.1	77.0*	153.7	4.1

Temperature and precipitation data from the Department of Hydrology and Meteorology (2013) and humidity data from NASA (2017).
*Humidity data for Bhimeshwar 47km SE of Okhaldhuga is shown as the closest location providing data

For comparison, a range of location data for regions of India and China that are close to the Nepalese boarder are shown in Table 4. In general, these locations show similar wind speeds, moderate humidity and lower June rainfall. Locations with available temperature variance are used for further analysis.

Table 4, Annual weather data

Location		Month	Average Temperature (°C)			Precipitation (mm)	Humidity (%)	Wind Speed (m/s)
			Mean	Min	Max			
INDIA	Gauhati	January	16.51	10.2	23.6	15.38	46.7	5.9
		May	33.46	22.6	31.1	10.81	66.9	5.1
	Patna	January	16.52	9.2*	22.9*	14.13	47.4	1.8
		May	31.65	25*	38.7*	40.93	64.6	3.0
	Lucknow	January	15.58	-	-	13.92	48.7	2.2
		May	33.17	-	-	13.72	43.1	3.4
CHINA	Pagri	January	-10.02	-	-	8.38	56.8	5.2
		May	2.17	-	-	89.23	83.1	4.1
	Shiquanhe	January	-14.28	-	-	20.3	65.9	6.1
		May	1.19	-	-	20.43	44.2	5.2
	Tingri	January	-13.51	-	-	11.14	61.5	3.3
		May	-0.15	-	-	54.32	80.1	2.6
	Lhasa	January	-5.75	-10.1	6.9	0.00	37.0	6.1
		May	8.09	5	19.3	38.71	55.9	4.6

Mean Temperature and precipitation from The World Bank Group (2017)
Max and Minimum Temperature from World Weather Information Service (2017)
Humidity and wind speed from NASA (2017)
*Max and min temperature from Gorakhpur

2.4. BUILDING AND SEISMIC CONSIDERATIONS

Existing architecture dictates how conditioning systems will perform. Building construction has evolved to utilise climate and available building materials without extensive external resourcing. This vernacular architecture is coupled with non-engineering techniques. Naturally available materials largely depend on climate regions; those typically available are summarised in Table 5.

Table 5, Available building materials based on Bodach, Lang and Hamhaber (2014) & Bonapace and Sestini (2003)

Region	Available Materials
Tarai	Wood, thatch and further biogenic material
Siwalik	Wood, thatch, lacustrine deposits, sand, gravel
Hills & Middle Mountain	Wood, Stones (schist, phyllite, gneiss, granite, limestone and slate)
High Mountain	Stones, rocks, mud

Earthquake risks are prominent in Nepal due to active faults throughout the region. Considering the seismic risk extrapolated from historic seismic data (Figure 8), it is possible for any region to experience a peak ground acceleration above 0.44g. Subsequently, any additional construction such as a trombe wall should be designed to withstand seismic activity.

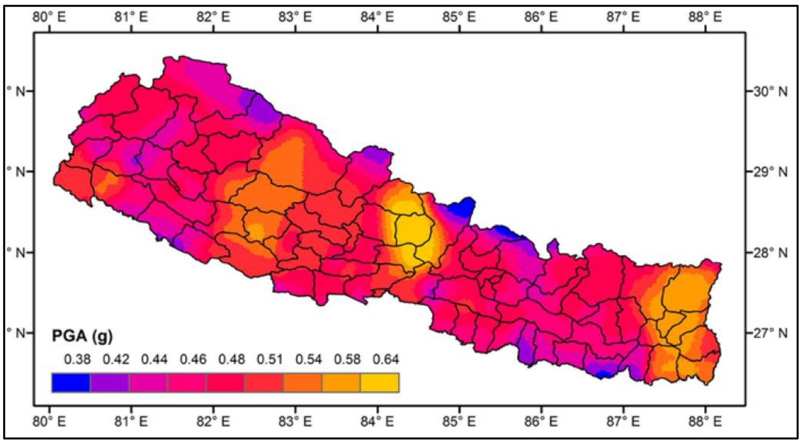


Figure 8, Seismic hazard at 5% probability of exceedance in 50 years (Chaulagain, Rodrigues, Silva, Spacone, & Varum, 2015)

3. IDENTIFYING APPROPRIATE TECHNOLOGY

3.1. Building and Climate Considerations

Comfort limits are displayed in Appendix 9.6 as an acceptable range of operative temperature for each location depending on the humidity (from Figure 1). This should be achievable over a standard 6 hour work or school day, expected to start around 10am (Himalayan Learning, 2017). Based on Nguyen and Reiter's chart (Figure 6) to meet climate comfort needs, the use of evaporative cooling may not be sufficient for cooling in Nepalgunj, while passive heating should meet heating demands in Okhaldhunga.

It is expected that storage of electrical energy will be too expensive for the target purpose. This design will attempt to incorporate direct passive heating with ventilation potential (see Figures 4 & 5). Additionally, a building model has been defined and with heat properties considered.

To develop a base building model, a number of 'non-engineered' principles for building constructions are identified (Smart Shelter Research, 2016) and given in Appendix 9.7. These are foremost applied to the project partner, Smart Shelter building constructions. Smart Shelter buildings are the main target for this research and therefore, the base case building profile is largely dependent on these principles as described in Table 6. It is assumed that regions around Nepal will also have similar construction principles.

Table 6, Base case building design

Feature	**Reasoning**
Gable Roof	Easy construction and common in Nepal
Square perimeter	Optimal shape efficiency vs. material (and complies with rule 4.a.)
6m lengths	Represents best practice maximum free span (rule 4.b.)
2.5m wall height	Within recommended maximum
Unsegmented space	Presents the most basic design and an open classroom space
Brick support walls	Brick/ stone with mud and cement mortar construction represents 44.21% and 17.57% of buildings in Nepal (Central Bureau of Statistics, 2012)
Single door and Window	A probable minimalist design. Should not exceed 50% wall surface and 60cm from corners (rules 8.a & 8.b.)
No added insulation	For base case, insulation can be considered later in analysis
Unobstructed south facing orientation	Optimises the potential irradiance on trombe wall

3.2. Cover and Wall Properties

The results strongly depend on the optical properties of the cover and wall. It is assumed that the cover will not significantly affect the stiffness of the wall structure. Therefore, in any seismic event the total displacement through the cover will depend on the building stiffness and anchorage (Figure 9). The cover will ideally deform without breaking. Materials for the cover can therefore be compared by their properties relating to elongation at break, ignoring internal vibration. Table 7 provides material properties of transparent materials with approximate costs, neglecting availability and shipping. Results from models indicate that material transmissibility is directly proportional to cover cost per area due to the linear relationship between output heat and cover transmissibility, assuming an unconstrained area. Also neglected are joining and fitting costs, although it is possible that 12.5m will consist of multiple panels. Other factors not considered are the material UV stability and toxicity as well as wind, vibration or other potential loads.

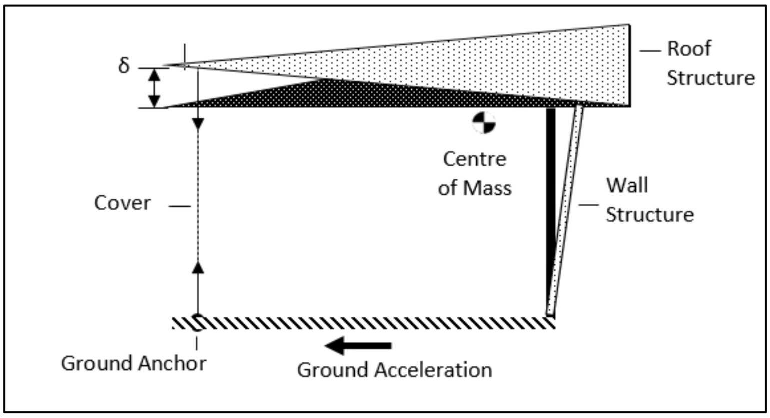


Figure 9, Illustration of seismic effects on cover

Table 7, Cove material comparison table

Material	Thickness of Sample (mm)	Light Transmission (%)	Thermal Conductivity (W/m·K)	Elongation at Break (%)	Approximate Cost for 12.5m^2 (AUD)
PVC	3	90[1]	0.21[1]	3-10[2]	166[3]
Glass	12	84[2]	1.1[2]	4.8[2]	675[4]
PEVA	-	89[1]	-	-	25[3]
Polyethylene	0.11	70-90[2]	0.02-0.29[2]	125[2]	14[5]
PMMA	3	92[6]	0.189[6]	4[6]	430[7]

[1]Suntuf Trimdeck Leaflet (Palram, 1997)
[2]Matweb Material Property Data (2017)
[3]Bunnings Warehouse Online Catalogue (2017)
[4]DIY Glass Fence/Balustrade (DIY Glass, 2017)
[5]Plastic Clear Polythene Cover (Londark Co., 2017)
[6]Perspex Cell Cast Acrylic (2017)
[7]Acrylic Clear Perspex (Acrylics Onilne Printing, 2017)

4. METHODOLOGY

4.1. Overview

Figure 10 illustrates the simulation overview roughly comprising of a setup, steady state and transient analysis. This approach was extended from Tarazi (1991), with a steady state analysis adapted from Duffie and Beckman (1991). The steady state model is an itterature solution approach determining heat in the wall and heat delived through fluid flow. This was used to update the toal heat into the wall and the room temperature across a given time period.

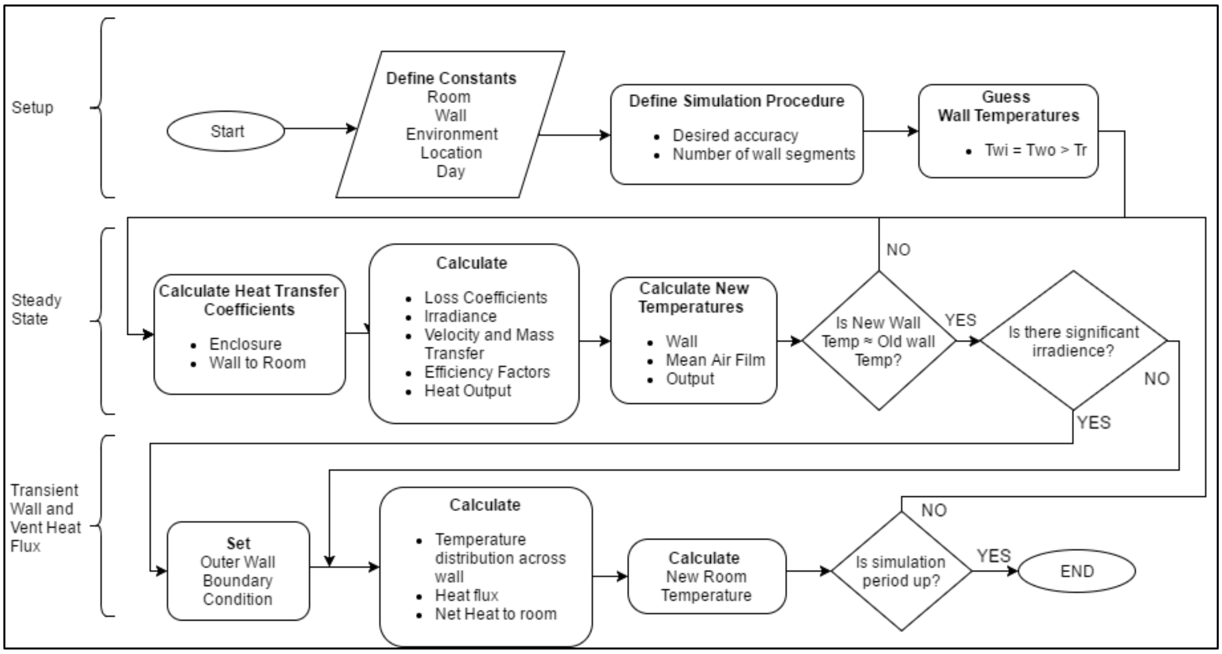
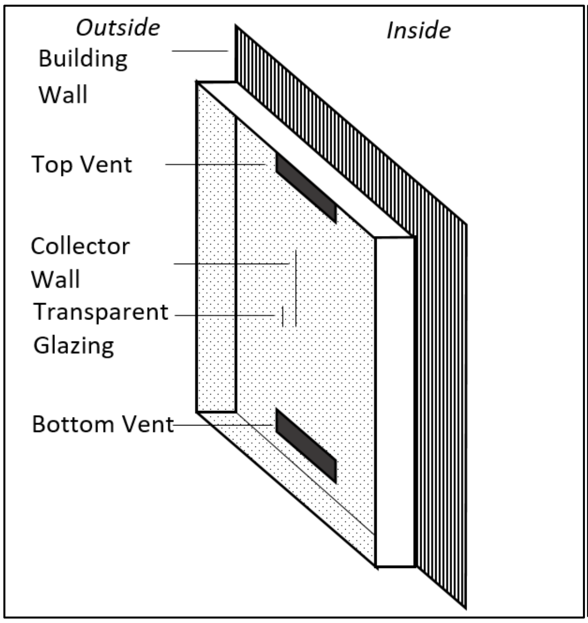


Figure 10, Method of transient system analysis

4.2. Steady-State Update

The approach was set up as a flat plate collector receiving radiation though glazing. This is part of an enclosure or air-gap, with vents at the top and bottom that cycle inside air. The system is shown in Figures 11 & 12. The heat was found as a function of temperatures, heat losses and available irradiance. This model was extended from Tarazi (Equation 1) to account for significant differences between the room and atmospheric temperatures (Equation 3).



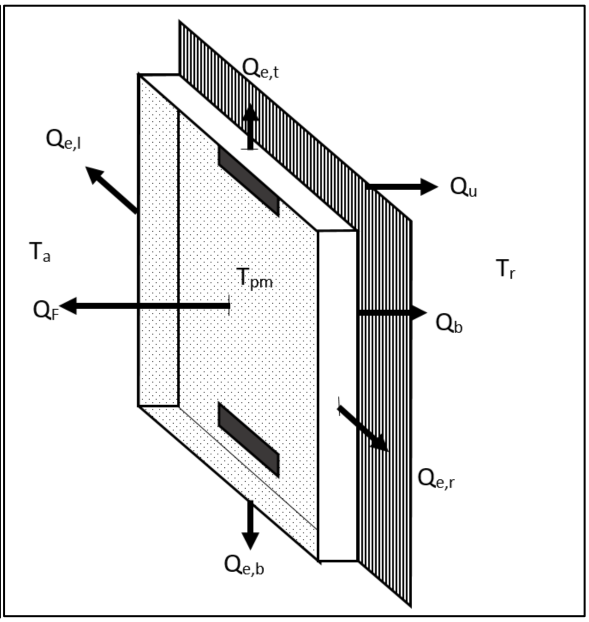


Figure 11 (left), Components of the trombe wall system and Figure 12 (right), heat fluxes and temperatures within trombe wall model

$$Q_u = A_c\left(S - U_{FE}\left(T_{pm} - T_a\right) - U_b\left(T_{pm} - T_r\right)\right) \quad (3)$$

Where:

Q_u – Useful heat delivered by vents (W)
A_c – Collector wall area (m^2)
T_a – Ambient Temperature (K)
U_{FE} – Heat loss coefficient from the front and edges = $U_F + U_{E,t}$

T_{pm} – Mean absorber plate temperature (K)
T_r – Room temperature (K)
U_b – Heat loss coefficient from back
S – Solar radiation absorbed per unit area absorber (W/m^2)

Assumptions:

1. Steady flow
2. 1D heat transfer,
3. Temperature gradients across wall length are negligible
4. Linearised radiative heat loss
5. No additional heat or mass transfer
6. Negligible thermal resistance across the cover
7. Air properties can be linearly interpolated from tabulated data
8. Irradiance is uniform across collector wall area
9. Directionality of radiation does not affect cover or wall optical properties
10. The air gap distance is uniform between the wall and cover
11. No significant restrictions to the air flow

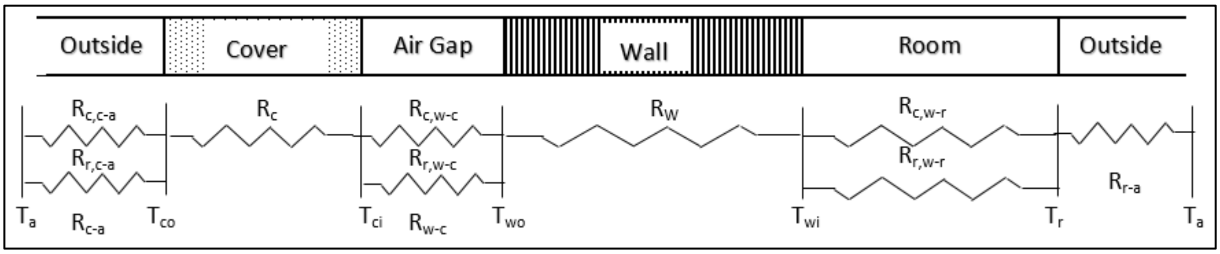


Figure 13, One-dimensional heat transfer resistances though trombe wall model

The glazing resistance was considered significantly lower than other components. Glass of thickness 3mm will have a resistance less than 5% of the convective resistance to atmosphere (Appendix 9.8). Therefore, the inner and outer glazing temperature (T_{ci} & T_{ci} respectively) will be equal (T_c).

Radiation heat transfer was linearised by Equation 11 (Duffie & Beckman, 1991). The heat transfer resistance from the wall to the cover was then found (Equation 6).

$$q_{loss,f} = \left(h_{c,wo-c} + h_{r,wo-c}\right)\left(T_{wo} - T_c\right) \tag{4}$$

$$h_{r,wo-c} = \frac{\sigma(T_{wo} + T_c)\left(T_{wo}{}^2 + T_c{}^2\right)}{\frac{1}{\varepsilon_{wo}} + \frac{1}{\varepsilon_c} - 1} \tag{5}$$

$$R_{wo-c} = \frac{1}{h_{c,wo-c} + h_{r,wo-c}} \tag{6}$$

The resistance from the glazing to the atmosphere in Equation 9 was simplified by assuming the sky and atmospheric temperatures are equal (T_s = Ta) from Equation 7.

$$h_{r,c-a} = \frac{\sigma\varepsilon_g(T_c + T_s)\left(T_c{}^2 + T_s{}^2\right)(T_c - T_s)}{(T_c - T_a)} \tag{7}$$

$$h_{r,c-a} = \sigma\varepsilon_g(T_c + T_a)\left(T_c{}^2 + T_a{}^2\right) \tag{8}$$

$$R_{c-a} = \frac{1}{h_{c,c-a} + h_{r,c-a}} \tag{9}$$

The heat transfer coefficient to the atmosphere was given from the natural convection outside and was calculated by Equation 10 (Watmuff, Charters, & Proctor, 1977). The total front heat loss coefficient was then determined (Equation 11).

$$\mathrm{h_{c,c-a}} = 2.8 + 3.0\mathrm{V} \tag{10}$$

Where: V – wind speed across outer surface (m/s)

$$U_f = \frac{1}{R_{wo-c} + R_{c-a}} \tag{11}$$

The heat transfer from the back was be calculated in a similar manner (Equation 14). This assumed radiative heat transfer from the wall to the room was negligible compared to convection as the wall the room temperatures are relatively similar. The convective heat transfer from the wall to the room was be found by Equation 23 with a Nusselt number determined in Equation 26.

$$R_{wo-wi} = \frac{w_t}{w_k} \tag{12}$$

$$R_{c,wi-r} = \frac{1}{h_{c,wi-r}} \tag{13}$$

$$U_B = \frac{1}{R_{wo-wi} + R_{c,wi-r}} \tag{14}$$

An efficiency factor 'F'' in Equation 15 has been defined by the useful energy gain compared to the gain if the collector and fluid temperature were the same.

$$F' = \frac{h(2h + U_{FE} + U_B)}{2(h + U_{FE})(h + U_B)} \tag{15}$$

A second factor, 'F_R' is defined by the actual useful energy gain compared to the gain if the entire system was of uniform temperature (Equation 16).

$$F_R = \frac{\dot{m}C_p\left(T_{fo} - T_{fi}\right)}{A_c\left[S - U_{FE}\left(T_{fi} - T_a\right) - U_b\left(T_{fi} - T_r\right)\right]} \tag{16}$$

The heat delivered by the vents was found in Equation 17 & 18.

$$Q_u = A_c F_R\left(S - U_{FE}(T_i - T_a) - U_b(T_i - T_r)\right) \tag{17}$$

$$S = c_t w_a I \tag{18}$$

New temperature estimates were then formulated. The mean wall temperature was found from both Equations 17 & 18 defining 'Q_u', eliminating 'S' shown in Equation 19.

$$T_{wo} = T_i + \frac{Q_u(1 - F_R)}{A_c F_R(U_{FE} + U_B)} \tag{19}$$

The mean film temperature is determined through a similar analysis, in Equation 20.

$$T_{fm} = T_i + \frac{Q_u\left(1 - \frac{F_R}{F'}\right)}{A_c F_R(U_{FE} + U_B)} \tag{20}$$

The mean velocity of the flow was then found by resolving viscous forces in Equation 21 (Tarazi, 1991).

$$V = \sqrt{\frac{2gw_l}{8\left[\frac{A_g}{A_v}\right]^2 + 2} \cdot \frac{T_{fm} - T_r}{T_{fm}}} \qquad (21)$$

The outlet temperature was found though a simple heat relationship in Equation 22.

$$T_o = T_i + \frac{Q_u}{\dot{m}C_p} \qquad (22)$$

4.3. Heat Transfer Coefficients

Heat transfer coefficients dictate much of the available thermal transfers within the system. The heat transfer coefficient from the hot collector wall to the cover was determined through an appropriate Nusselt number with dependence on Rayleigh number and the aspect ratio of the enclosure cross section (Equation 23). This is assumed to be an infinite cross-section with an adiabatic top and bottom (Figure 14).

$$\mathrm{h_{c,x}} = \frac{\mathrm{Nu_x\ k}}{\mathrm{D}}, \qquad (23)$$

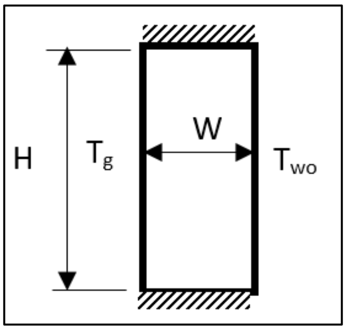


Figure 14, Diagram of air gap

As flow transitioned between different regimes, the Nusselt number was calculated though a piecewise function which takes experimental correlations from literature. Macgregor and Emery (1969) provide a correlation in an enclosure (Equation 24). This is valid for $10<H/W<40$ and $1<Pr<20$. Although prandyl numbers considered were around 0.7, the heat transfer coefficient "does have a strong additional dependence upon Pr [less than 1]"(Macgregor & Emery, 1969) and the relationship was assumed relevant.

$$Nu_W = \begin{cases} 0.42(Ra_W)^{0.25}Pr^{0.012}\left(\frac{H}{W}\right)^{-0.3}, & 10^4 < Ra_W < 10^6 \\ 0.046((Ra_W)^{\frac{1}{3}}, & 10^6 < Ra_W < 10^9 \end{cases} \quad (24)$$

$$Ra_x = \frac{g\beta(T_1 - T_2)x^3}{v^2} \cdot Pr \quad (25)$$

Where: T_1 – Hot wall temperature, T_2 - Cold parallel wall or the freestream fluid temperature

As the temperature was not constant across the wall height, this height was split into 15 segments and the average heat transfer coefficient taken. By assuming constant heat flux, wall temperatures were then interpolated from a mean temperature and lower boundary given as the room temperature.

The air properties were taken from a linear interpolation at the mean fluid temperature. Tabulated data for air at atmospheric pressure is given in Table 8.

Table 8, Air properties (Ghoshdastidar, 2012)

Temp (K)	**Cp x 10^3 (J/kg·K)**	**ρ (kg/m³)**	**v x 10^{-6} (m²/s)**	**k x 10^{-3} (W/m·k)**	**Pr**	**β x 10^3 (1/K)**
250	1.006	1.3947	11.44	22.3	0.720	2.884
300	1.007	1.1614	15.89	26.3	0.707	2.881
350	1.009	0.9950	20.92	30.3	0.700	2.880

The Nusselt number defining heat transfer to an open area was developed by McAdams (1954) for laminar flow and Crawford (1980) for turbulent flow in Equation 26.

$$Nu_L = \begin{cases} 0.59(Ra_L)^{\frac{1}{4}}, & 10^4 < Ra_W < 10^9 \\ 0.1(Ra_L)^{\frac{1}{3}}, & 10^9 < Ra_W < 10^{13} \end{cases} \quad (26)$$

4.4. Solar Irradiance

Assumptions:
1. Irradiance can be simplified to a unit value across useful wavelengths
2. Reflective radiation is negligible
3. Optical depth values can be linearly interpolated depending on latitude, longitude and elevation
4. Irradiance calculation for the 21st of a given month is representative of that month

The irradiance was found by utilising solar terrestrial equations and data outlined by ASHRAE (2013). The total irradiance, 'E_t' was found though Equation 27 from the beam, diffuse and reflective components incident on the wall surface ($E_{t,b}$, $E_{t,d}$ & $E_{t,r}$ respectively).

$$E_t = E_{t,b} + E_{t,d} + E_{t,r} \tag{27}$$

A conservative assumption was made that the reflective radiation was negligible. This is probable when reflecting surfaces are not visible by the receiving wall ($E_{t,r}$ = 0). Calculations were made for the 21st day of the month. A flow chart illustrating the calculation procedure is shown in Figure 17, with remaining equations given in Appendix 9.8. The inputs are highlighted in bold as:

- Day of the year
- Longitude of local standard time meridian
- Location longitude
- Location latitude
- Surface azimuth

It is important to note a relationship towards surface azimuth angle provided in Table 9.

Table 9, Surface orientations and azimuths, measured from south (ASHRAE, 2013, CH 14.10)

Orientation	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Surface azimuth ψ (°)	180	-135	-90	-45	0	45	90	135

This calculation depends on tabulated values of optical depths provided by ASHRAE for various locations. As no data is available within Nepal, these values were interpolated for 6 locations close to Nepalgunj or Okhaldhunga found in 10. Plots showing this relationship are found in Appendix 9.11.

Table 10, Location specific irradiance values

Location Nepal LSM = 86.33°E	**Month**	***Daily Solar Irradiance (kWh/m²/d)**	**Interpolated Optical Depths**	
			Beam	Diffuse
Nepalgunj (28.07°N, 81.62°E)	January	3.91	0.451	2.032
	May	7.28	0.673	1.602
Okhaldhunga (27.32°N, 86.50°E)	January	4.25	0.405	2.174
	May	6.48	0.620	1.576

*Horizontal daily solar radiation from NASA (2017)

Table 11, Locations used to interpolate optical depths

Location		Latitude °N	Longitude °E	Elevation (m)	*DSI January (kWh/m²/d)	*DSI May (kWh/m²/d)
INDIA LSM = 82.5°E	Gauhati	26.10	91.58	54	4.50	7.42
	Patna	25.6	85.1	60	4.18	6.90
	Lucknow	26.75	80.88	128	3.72	6.57
CHINA LSM = 120°E	Pagri	27.73	89.08	128	4.03	5.73
	Shiquanhe	32.50	80.08	4280	3.61	7.41
	Tingri	28.63	87.08	4300	4.28	5.34
	Lhasa*	29.67	91.13	54	4.5	6.66

*Lhasa was not considered close enough to use in interpolation but was used later for comparisons

Horizontal daily solar irradiance (DSI) values were used and compared to the daily solar irradiance to determine validity. The daily solar irradiance was assumed by a parabolic curve. Factors used to determine this curve were zero irradiance at sunrise and sunset, and the total daily irradiance equal to the integral between.

$$I_t = At^2 + Bt, \qquad for\ 0 < t < H_d \tag{28}$$

$$A = \frac{-6I_d}{{H_d}^3}, B = \frac{6I_d}{{H_d}^2} \qquad (29), (30)$$

Where: I_t – Instantaneous Irradiance (W/m^2) I_d – Total Daily Irradiance (W /m^2·d)
t - Time from sunrise (h) H_d – Number of daylight hours (h)

Figure 15 & 16 shows plots of this analysis for Okhaldhunga in January and May. This indicates the greatest component of irradiance as beam radiation, roughly matching parabolic approximation of DSI. The vector corrected irradiance is greatly reduced in May, due to large angles of incidence. Appendix 9.9 shows remaining locations with similar trends.

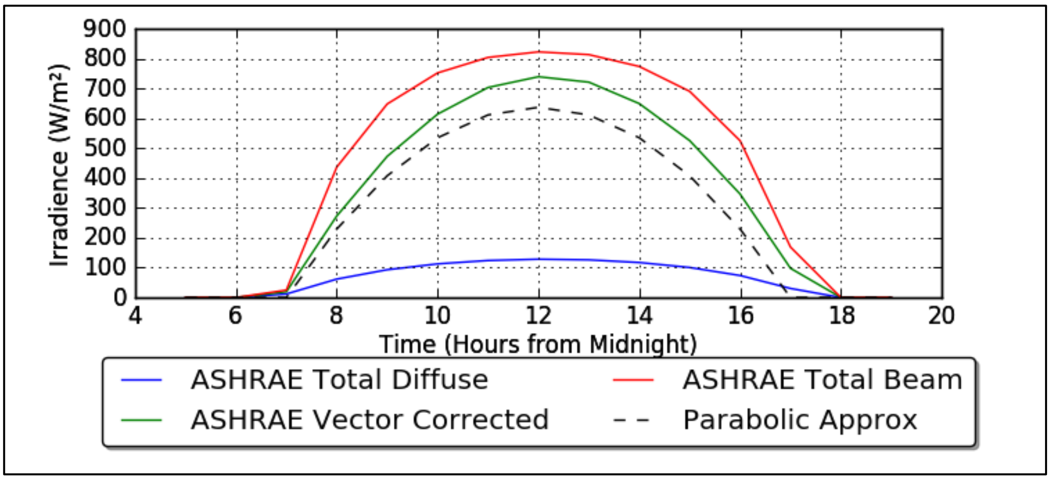


Figure 15, Irradiance comparisons for Okhaldhunga, January

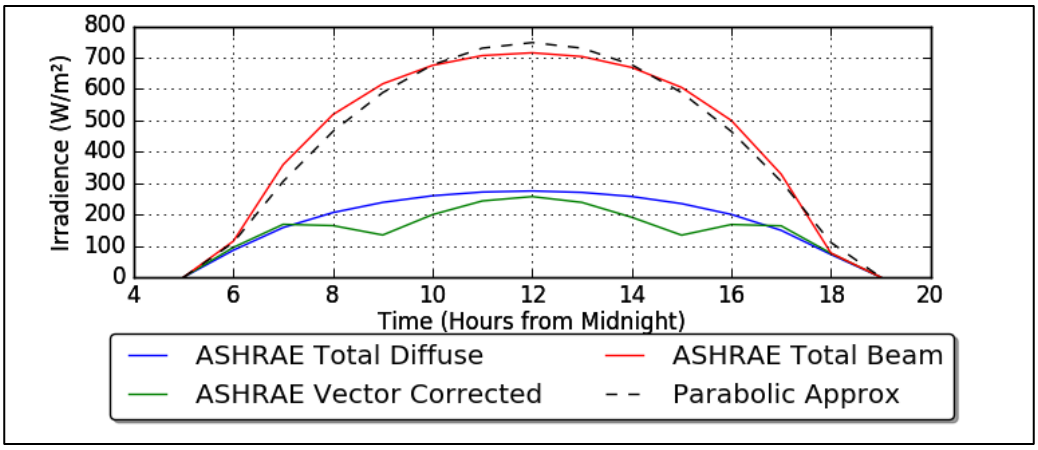


Figure 16, Irradiance comparisons for Okhaldhunga, May

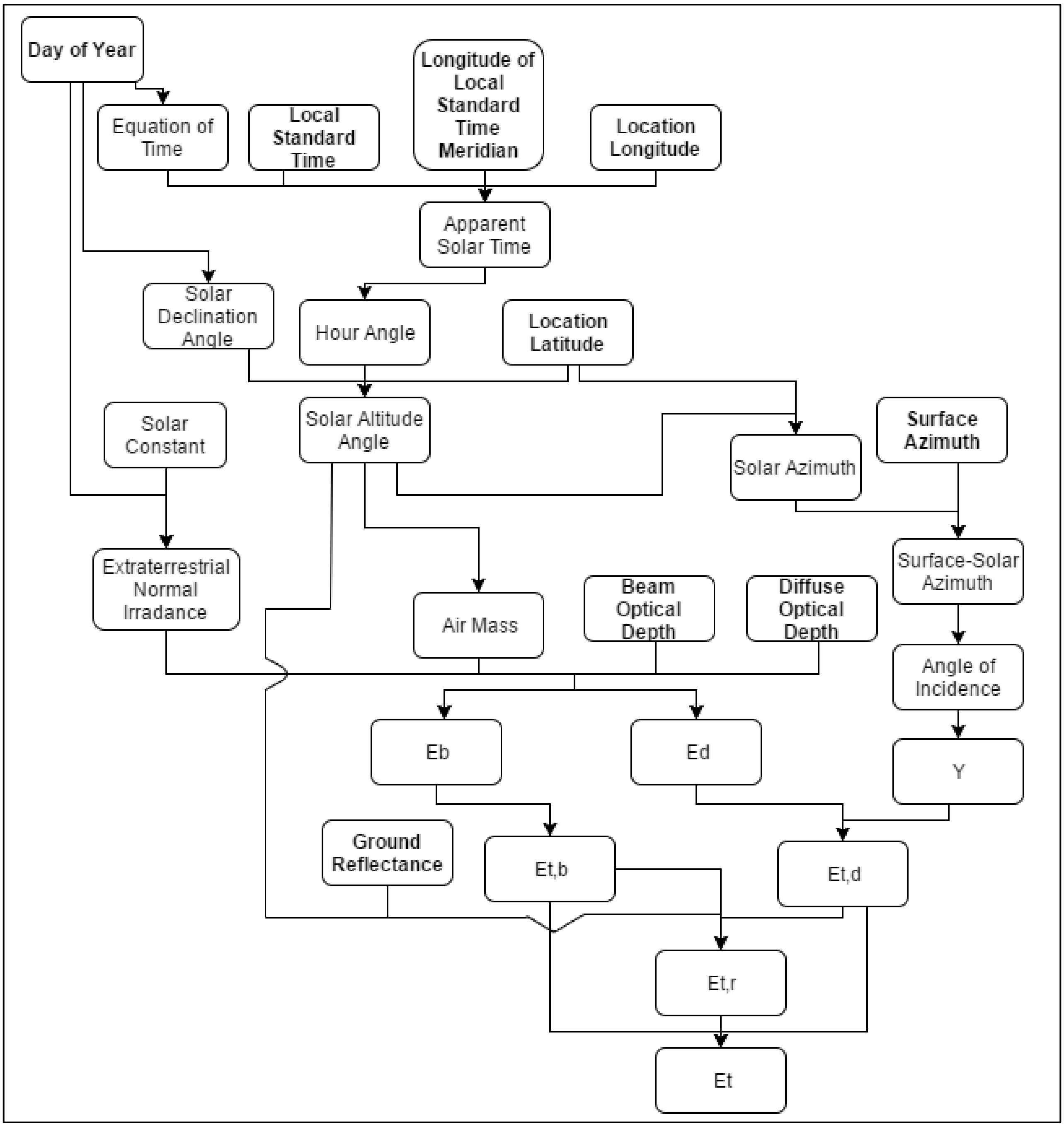


Figure 17, Summary of ASHRAE calculation procedure for solar irradiance

4.5. Transient Update Calculation

To determine the temperature distributions from the inner to the outer wall, the previous distribution, and the specific heat conductivity of the wall was required. This was iterated for each temperature 'T_i' where 'i' ranges from 1 to 'n' as the number of wall segments (Equations 31 & 32).

Assumptions:

1. Room temperature and heat transfer remains uniform within each hour interval
2. Heat transfer at wall boundaries can be linearised

$$C = \frac{k_w \Delta t \Delta x}{\rho_w C_p} \tag{31}$$

$$T_{i,t+1} = C\left(T_{i-1,t} + T_{i+1,t}\right) - (2C - 1)T_{i,t} \tag{32}$$

The convective heat transfer from the inner wall to the room was taken as part of the back heat loss coefficient. For convenience, this was linearised by considering a ghost segment temperature with equivalent conductive heat transfer in Equation 33.

$$T_{n+1} = T_{n-1} + \frac{2h_2 \Delta x}{k}(T_r - T_n) \tag{33}$$

Similarly, when irradiance was insignificant, the driving force for the outer wall temperature is conductive heat transfer from the front loss coefficient calculation in Equation 34.

$$T_0 = \frac{2h_1 \Delta x T_1 - kT_2}{2h_1 \Delta x - k_w} \tag{34}$$

The conducted heat transfer is constant across the wall between any 2 segments. This was found by Equation 35.

$$Q = \frac{k_w A_c (T_n - T_{n-1})}{\Delta x} \tag{35}$$

Under the modified design for ventilation, air extracted from a building has equivalent heat transfer according to the latent heat removed which is given in Equation 36 (ASHRAE, 2013).

$$q_s = Q\rho c_p \Delta T \tag{36}$$

Where:

q_s	is the sensible head load, W	Q	is the airflow rate, m^3/s
ρ	is the air density, kg/m^3	c_p	is the specific heat of air, J/(kg•K)
Δ	is the temperature difference between indoors and outdoors, K		

The change in room temperature was updated hourly by the heat into the room and the heat lost due to thermal resistance by Equation 37.

$$T_{r,t+1} - T_{r,t} = \frac{\Delta t \left(Q_{i,tot} - \frac{T_{r,t} - T_{a,t}}{r} \right)}{C_{p,r}} \tag{37}$$

The total heat into the room depended on the case analysed. The ambient temperature was varied hourly regarding the daily temperature profile (Appendix 9.5).

5. RESULTS AND DISCUSSION

5.1. Analysis Inputs

All results were obtained in Python from the calculations provided and properties listed below, unless otherwise stated. A sample of the Python script used to simulate is given in Appendix 9.14. The room thermal heat capacity was found from room dimensions and specific heat capacity with the density of air at 300K and a room area of 90m^2. Properties of the absorber wall were estimated for dark coloured brick, 2.5m high, 5m long and 0.3m thick. Edge losses were considered negligible. Considering a conservative total U-value of 4.8W/m^2·K with 4 walls (2.5m x 6m) a thermal resistivity was estimated to be 0.008K/W.

r = 0.008 (K/W)	$C_{p,r}$ = 105 (kJ/K)	ε_c = 0.75	ε_w = 0.90
ρ_w = 2400	$C_{p,w}$ = 900 (J/kg·K)	w_a = 0.90	k_w = 0.7
Orientation South			

5.2. Steady State and Optimisation Results

The systems steady state response was plotted to determine the heat delivered by the vents and the mass flow rate of air. This was used to optimise the characteristics of the air gap and vent size to use in transient simulations. Inputs for the steady state optimisation are given below.

I = 420W/m2	V = 0	T_a = 6.8°C	T_r = 10°C

Figure 18 and 19 plot the heat output vs. air gap and vent area respectively from the given parameters. A maximum heat out is reached around 4% vent area. The air gap becomes less significant above about 80mm, so 100mm was chosen as optimal.

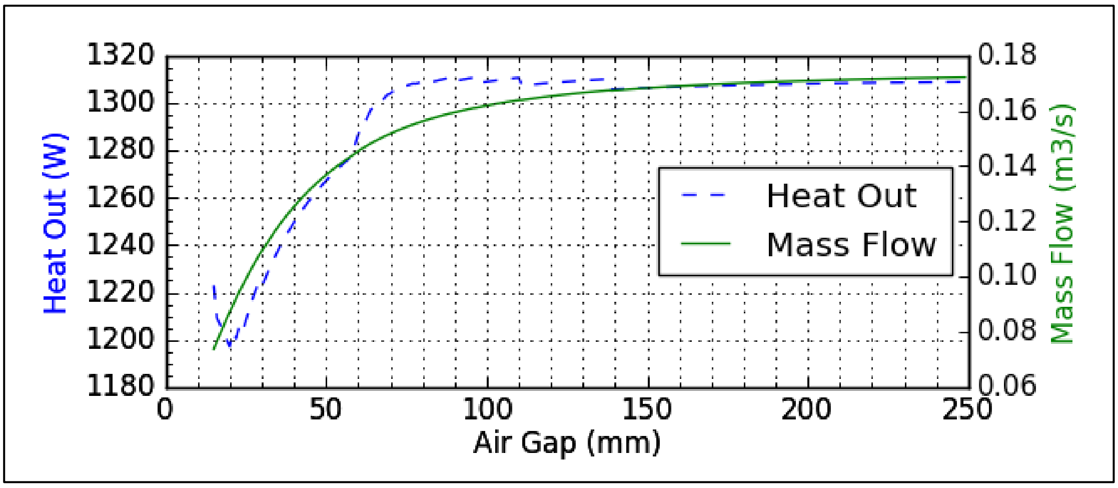


Figure 18, Heating air gap optimisation given 4% vent area

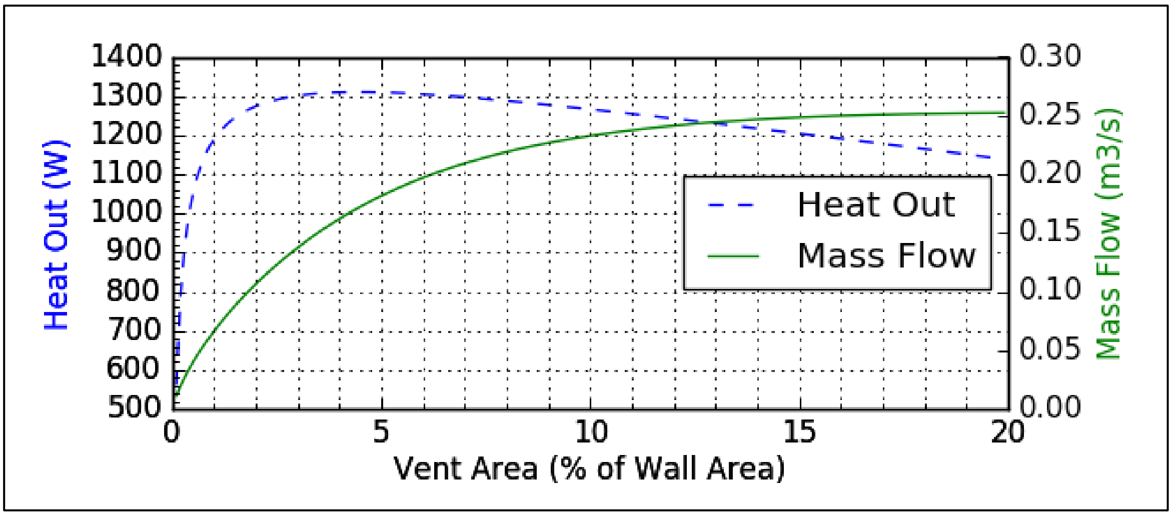


Figure 19, Heating vent area optimisation given 100mm air gap

Figure 20 and 21 plot the mass flow vs. air gap and vent area respectively, to given parameters. The limits of the heat transfer coefficient used in Equation 24 dictate an air gap between 62.5-250mm. An air gap of 250mm was chosen as large values should not greatly increase the flow rate, and the provided ventilation found in transient results still exceeds standards. The subsequent optimal vent area is therefore about 30%, recognising the limit of opening to 50% of a wall area in Smart Shelter principles for constructions (2016).

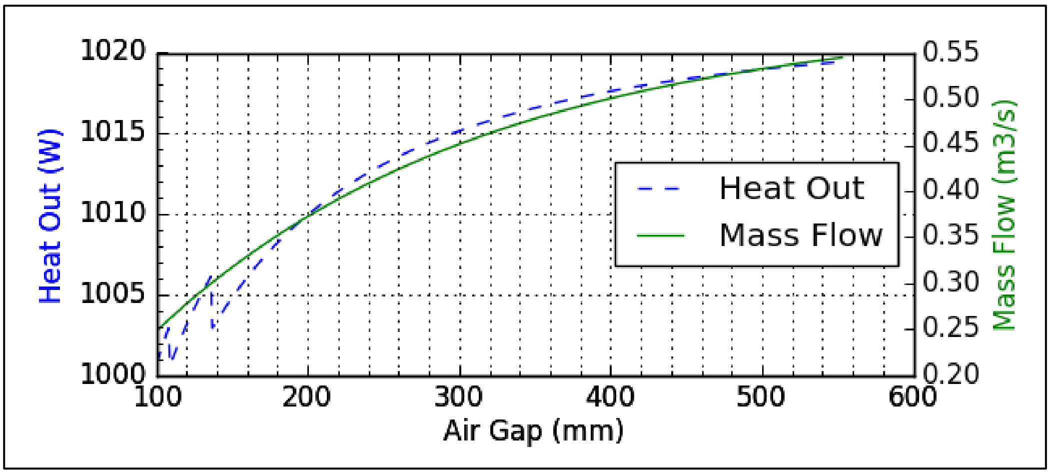


Figure 20, Ventilation air gap optimisation given 30% vent area

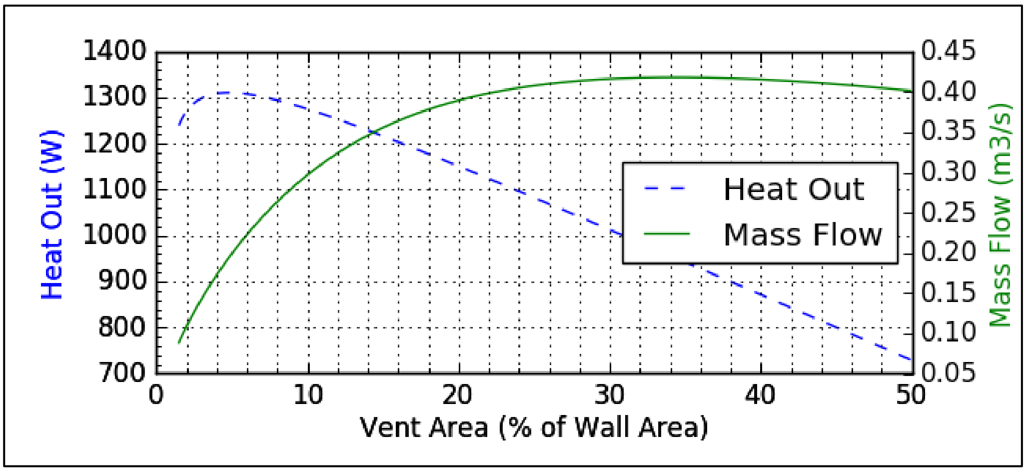


Figure 21, Ventilation vent area optimisation given 250mm air gap

Also of interest were the steady state performance of additional design parameters including the cover transmissibility, wall emissivity and wall absorptivity. Figures 22, 23 and 24 show these dependencies for an air gap of 100mm and a vent area of 4%. The wall emissivity shows lowest significance with transmissibility and absorptivity reasonably linear in providing available solar irradiance.

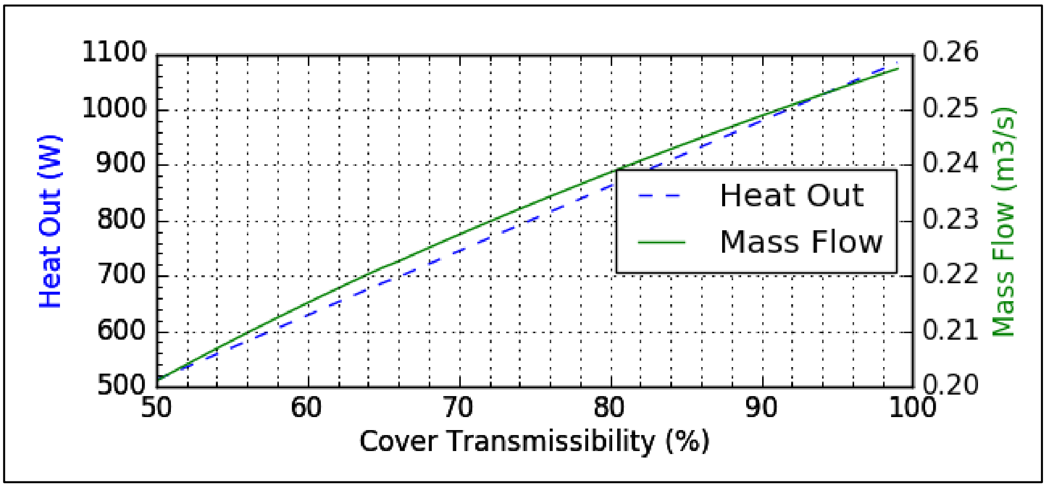


Figure 22, Performance vs. cover transmissibility with 100mm air gap and 4% vent area

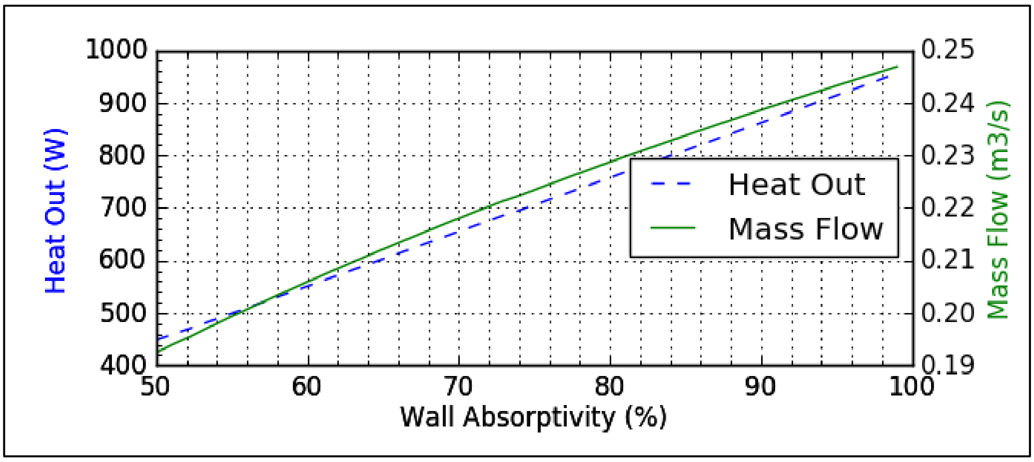


Figure 23, Performance vs. wall absorptivity with 100mm air gap and 4% vent area

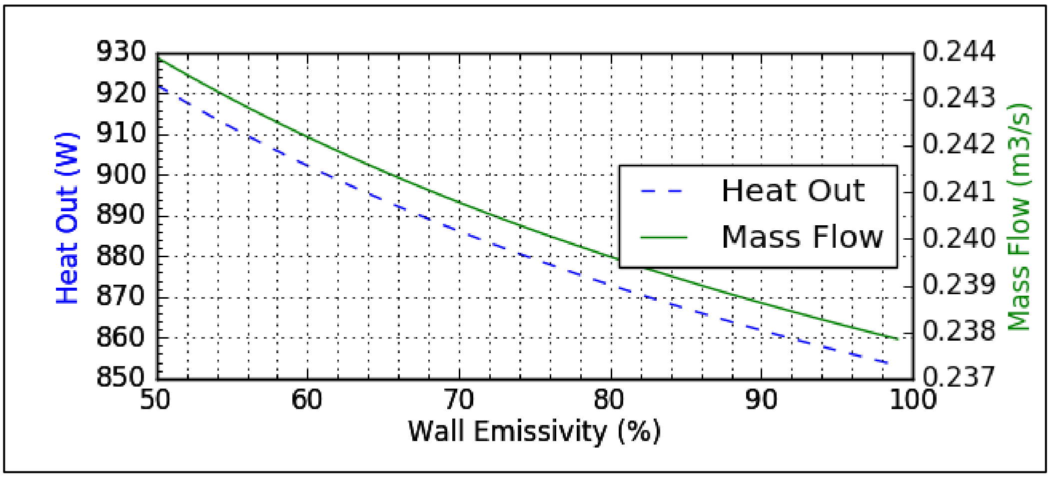


Figure 24, Performance vs. wall emissivity with 100mm air gap and 4% vent area

5.3. Transient Location Results

The following plots provide simulation results from a base case that has no heat transfer from a trombe wall, as well as a trombe wall system simulation. The inputs are as stated in Section 5.1 with irradiance from ASHRAE calculations, and an optimised 4% vent area and 100mm air gap. The start is given at 00:00 LST while vertical lines indicate a Boolean variable separating hours with significant irradiance (i.e. daylight hours), labelled by the output 'SUN'. Results from the base case consistently show the room temperature slightly delaying the oscillatory behaviour of the ambient temperature with lower amplitude. Results plot the time vs. ambient and room temperatures as well as the heat or ventilation provided by the vents.

Figure 22 shows Okhaldhunga heating results in January, plotted over 3 days. This shows that a steady temperature oscillation had been reached. The results show a significant increase from the base temperature with a maximum increase in room temperature of 11.55 °C at any given

time from the base scenario. The system maintains a room temperature above 20.5°C for 6 hours for which is the approximate recommended comfort at an average May humidity of 44%.

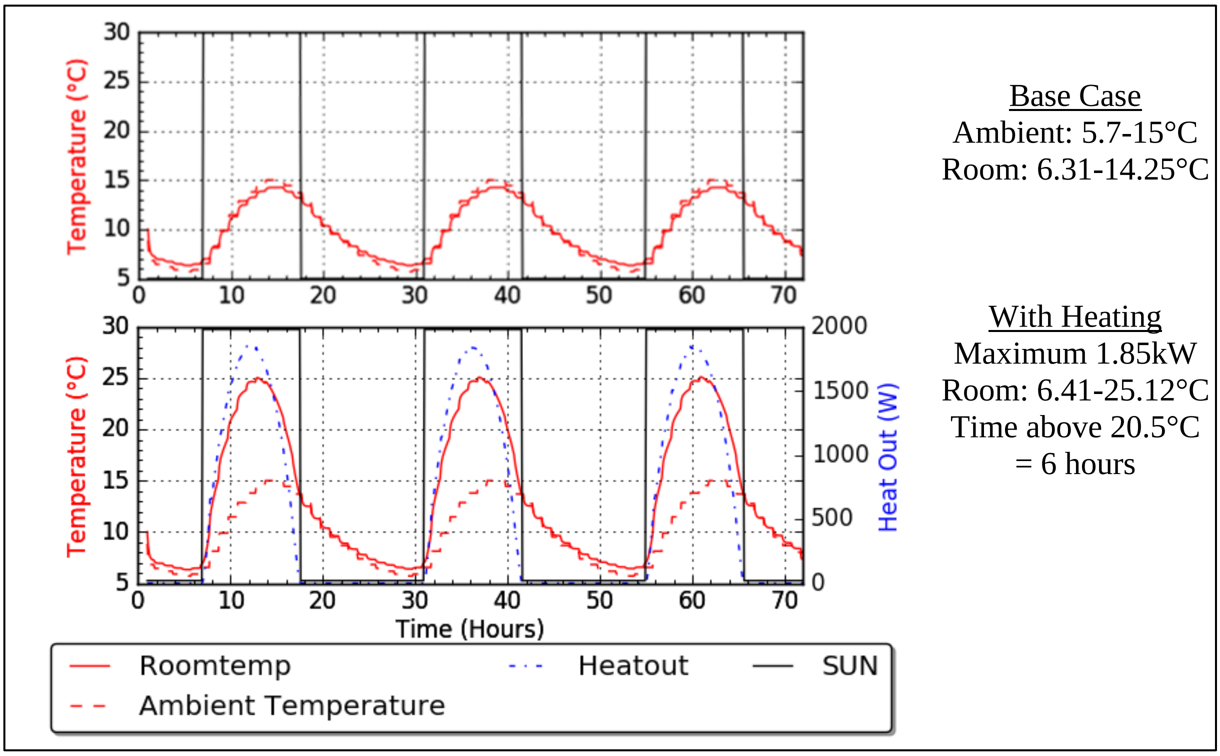


Figure 25, Base case (top) and trombe wall system (bottom) for Okhaldhunga heating in January

Remaining results are plotted for the 3rd day of simulation (hours 48-72) to ensure steady results. Figure 26 shows the same system operating in summer (May). A maximum of 4°C increase in temperature is reached however, a maximum comfortable temperature is exceeded. This is especially due to the high humidity. The peak heat out is less than the January case due to lower irradiance, as recognised in Section 4.4.

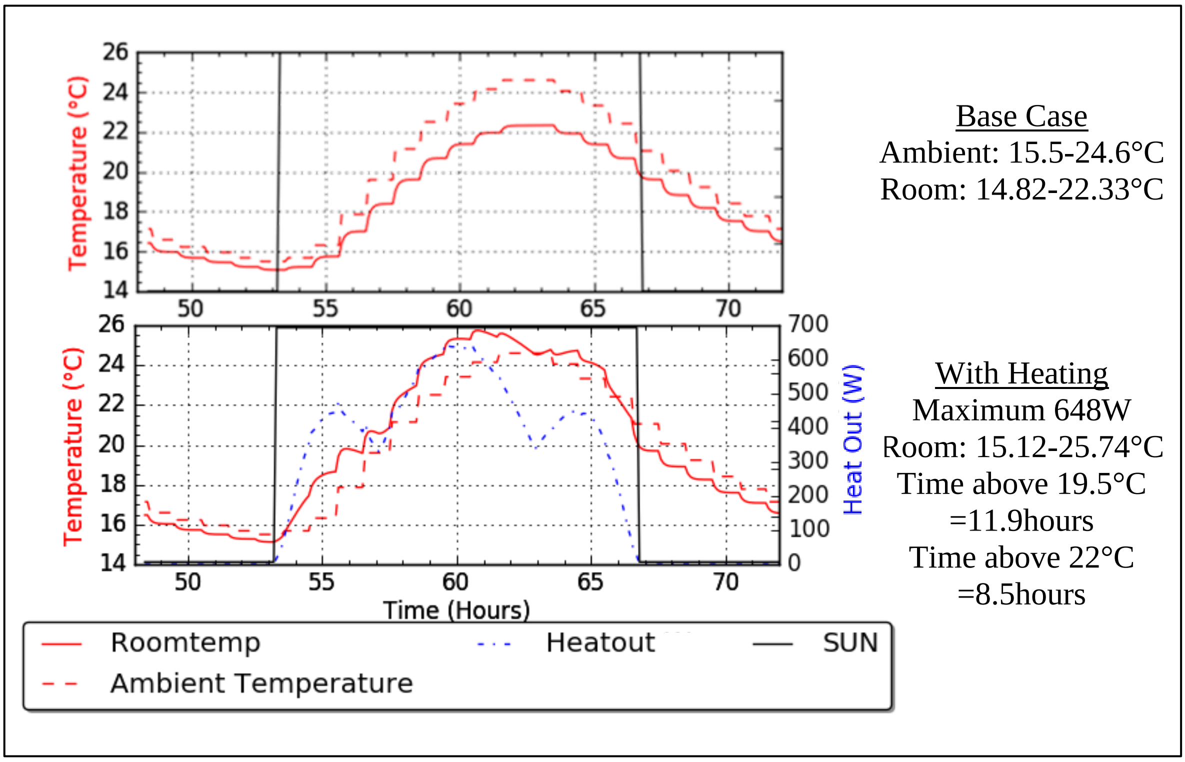


Figure 26, Base case (top) and trombe wall system (bottom) for Okhaldhunga heating in May

Figure 27 shows the system in Nepalgunj during January with a maximum temperature increase of 11.11°C. It is noted that room temperatures exceed upper comfort limits. This may be improved by operable vents or a smaller trombe wall size.

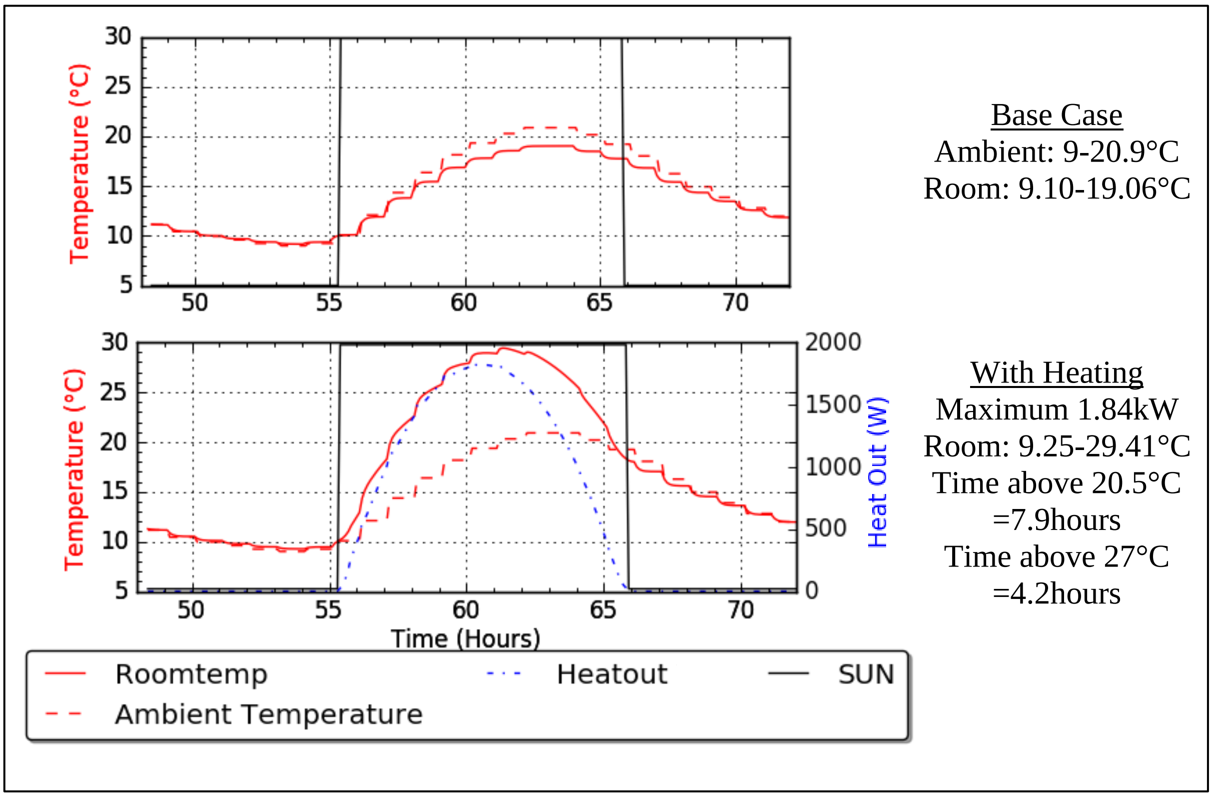


Figure 27, Base case (top) and trombe wall system (bottom) for Nepalgunj in January

If the same system is used in May, there is an increase in temperature of 3.35°C from a base case. This is unfavourable overall and it is recommended to use the ventilation case shown in Figure 28. This alters the upper vent open to the atmosphere considering Equation 36. A maximum increase of 2.89°C is then reached however, temperatures exceed maximum comfortable limits. The ventilation case achieves 12 hours above a recommended 0.087m^3/s flow rate.

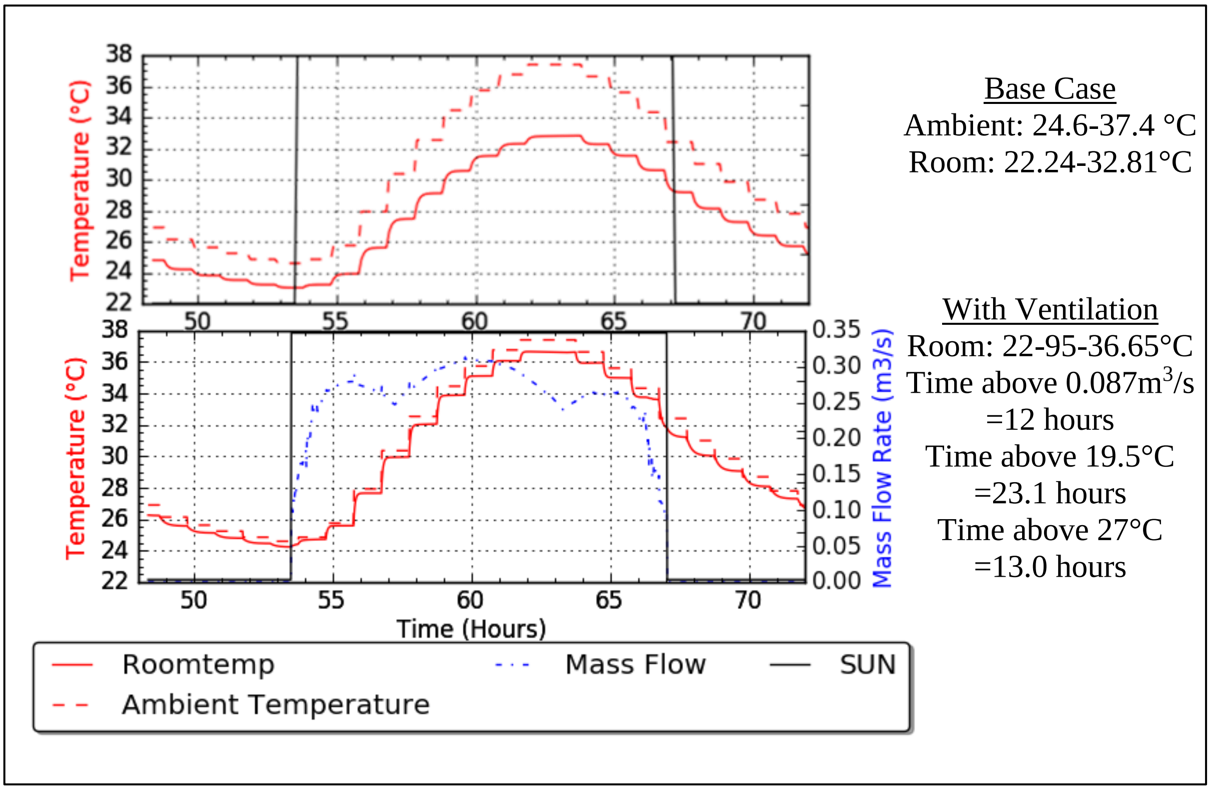


Figure 28,Base case (top) and trombe wall system (bottom) for Nepalgunj ventilation in May

5.4. Room Characteristic Dependency

To find conditions where the system is effective, the system defined in 5.1 was varied for room thermal resistance and heat capacity until 6 hours above the minimum comfort temperatures was reached. The time where this comfort is achieved is typically between 10am and 4pm. Effects of room characterises to temperature profiles can be seen in Appendix 9.13, with a higher heat capacity slightly delaying the time where comfort is reached. Figure 29 shows this analysis indicating a low dependency of thermal capacity.

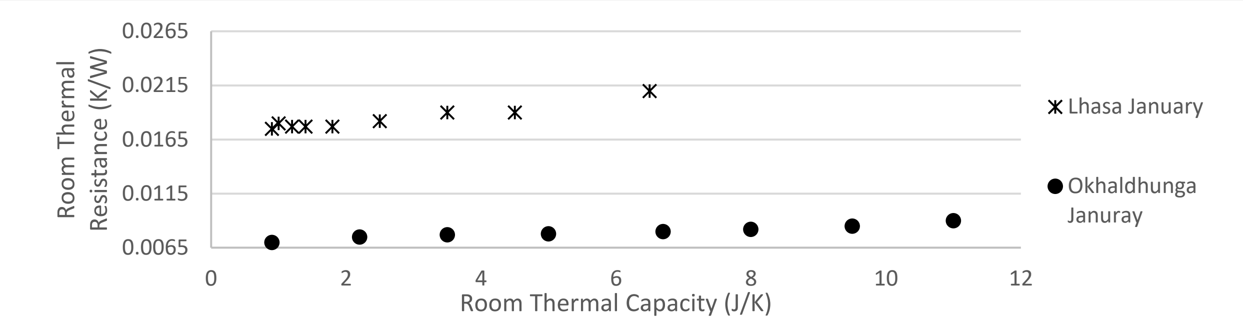


Figure 29, Room characteristics for minimum January comfort

Further analysis was conducted for 5 locations and room thermal resistances to determine a minimum wall length to achieve at each location, shown in Table 12. The wall height was 2.5m with a room heat capacity of 105kJ/K. Bounds of the analysis were set by a wall length limit of 5m, with thermal resistances considered reasonable between 0.03 and 0.004 K/W. Ventilation results for Lhasa were omitted as minimum comfort temperatures under ventilation operation was not met within bounds and system characteristics. A large dependency between wall length and thermal resistance was seen when achieving minimum comfort temperature in January. When considering the minimum ventilation in May, this dependency is small and mostly insignificant.

Table 12, Wall length to achieve comfort

Location	**Thermal Resistance (K/W)**	**Minimum Characteristics for January (6h above minimum temperature)**	**May Ventilation Conditions (6h above 0.087m^3/s)**	
		Wall Length (m)	Wall Length (m)	Time Above Max (h)
Okhaldhunga	0.008	5	3.9	6.0
	0.019	2.2	3.9	5.9
	0.03	1.4	3.9	5.9
Nepalgunj	0.004	2.5	4.1	14.9
	0.008	1.5	4.0	13.1
	0.012	1	4.1	12.3
Lhasa	0.012	5	*Ventilation does not achieve minimum climate comfort*	
	0.03	3.4		
	0.05	2.1		
Patna	0.004	0.1	3.5	23.1
Gauhati	0.004	*No heating required*	4.0	15.1

6. CONCLUSION

Results of the analysis show potential for this system to achieve climate comfort in clear sky conditions. The most promising results were shown in Okhaldhunga for a system able to alter the upper vent between inner and outer exhaust. This achieved 6 hours within temperature comfort limits for January and 6 hours of ventilation in May. However, due to the high humidity, a maximum comfort temperature was sill exceeded. The cost of the cover is expected to range from 14 AUD for $12m^2$ of polyethylene, however further analysis of structural application and additional components will be required for a full cost analysis.

Results display similar trends and results to the paper by Tarazi (1991). This is evident when modelling similar inputs of irradiance, wall size and optical characteristics, and comparing optimal heating characteristics of 100mm air gap and 4% delivering around 1.3kW.

While results were based from 3 days of clear sky, there were small variances between days. Therefore, a single day of clear sky should achieve similar outcomes. This is especially important for locations with high precipitation, where precipitation events will greatly reduce the solar irradiance and decrease the trombe wall performance. Models for May operation showed a lower maximum heat output compared to January due to larger incident angles around midday. This is despite having greater daily solar irradiance on unshaded horizontal surfaces. It is expected that this could be utilised for passive applications in summer months, which require lower heating demands than in winter. For example, incorporating large roof eaves would effectively shade the trombe wall in summer from beam radiation during the most solar intense times of the day.

For most summer conditions, ventilation modelling suggested an increase in room temperature from a base case, resulting in higher temperatures and time above comfortable levels. This is expected to be less extreme, due to limitations of the model regarding additional heating into the building. This additional heating may arise from radiation absorbed (and consequently conducted into the room) though other wall surfaces as well as greenhouse heating effects from windows.

Other model limitations may propagate from linearisation assumptions and property data. Dependencies of this angle of incidence to transmissibility and absorptivity of materials have also been neglected in this analysis. Consequently, large angles will further reduce the useful solar radiation to the system.

7. FURTHER WORK

It is recommended that further progress is made towards implementing trombe wall designs into explored regions. The system was found to be especially useful in winter and cold climates such as in Lhasa. Further analysis should be made towards the ventilation potentials by improving building models or identifying buildings where the room temperature greatly exceeds the ambient temperature, and ventilation will have a positive cooling effect.

To understand the applicability of results, methods of refining building resistances that are dependent on construction properties or recorded data should be explored. Additionally, understanding materials used in a trombe wall design, and other potential structural loads with possible alleviations should be considered. It may be ideal to find a less stiff material as to not affect the building dynamics in a seismic event. Anchorage points may also be utilised to break under extreme events.

Overall, while the model in this report should represent reasonable assumptions and shows promising results, a physical method to validate the design will be needed before any large invests are made. Additionally, identifying a community specific acceptability range for climate comfort will ensure the needs of the community are effectively met during implementation. The report model should be used to optimise a passive system design specific to a given location with considerations such as:

- Midday shading through roof overhang or external walls
- Operable vent modelling
- Optimal flow rate vs. heating characteristics
- Surface azimuth angles to utilise greater morning or evening heating

A full cost analysis is recommended, furthering the material identification in the scope of this report. An additional analysis should include, suitability and recommended thickness of cover materials, joining and anchorage methods as well as potential for operative vents within the wall and cover. This will ensure a design that can be built with similar characteristics while identifying other economic, social and environmental factors.

Apart from the trombe wall design, other conditioning methods such as evaporative cooling, dehumidification or air expansion cooling can have a large effect on climate comfort, depending on humidity as well as comfortable temperature limits.

8. REFERENCES

Acrylics Onilne Printing. (2017). Acrylic Clear Perspex 1200 x 2440 x 3mm Cast Sheet UV Rated. Retrieved from http://www.ebay.com.au/

ASHRAE. (2004). *ASHRAE standard : thermal environmental conditions for human occupancy*. Atlanta, GA: American Society of Heating, Refrigerating Air-Conditioning Engineers.

ASHRAE. (2013). *2013 ASHRAE handbook: fundamentals. (SI ed.)*. Atlanta, GA: American Society of Heating, Refrigerating Air-Conditioning Engineers.

ASHRAE. (2016). Standard 62.1-2016- Ventilation for Acceptable Indoor Air Quality. Atlanta, GA: American Society of Heating, Refrigerating Air-Conditioning Engineers.

Bajc, T., Todorović, M. N., & Svorcan, J. (2015). CFD analyses for passive house with Trombe wall and impact to energy demand. *Energy and Buildings, 98*, 39-44.

Bako-Biro, Z., Clements-Croome, D. J., Kochhar, N., Awbi, H. B., & Williams, M. J. (2012). Ventilation rates in schools and pupils' performance. *Building and Environment, 48*, 215-223.

Bodach, S., Lang, W., & Hamhaber, J. (2014). Climate responsive building design strategies of vernacular architecture in Nepal. *Energy and Buildings, 81*, 227-242.

Bonapace, C., & Sestini, V. (2003). *Traditional Materials and Construction Technologies Used in the Kathmandu Valley*. SP, France: United Nations Educational, Scientific and Cultural Organization,.

Bunnings Warehouse. (2017). Online Catalogue. Retrieved from http://www.bunnings.com.au

Camargo, J. R., Ebinuma, C. D., & Silveira, J. L. (2005). Experimental performance of a direct evaporative cooler operating during summer in a Brazilian city. *International Journal of Refrigeration, 28*(7), 1124-1132.

Central Bureau of Statistics. (2012). *National Report*. Retrieved from Kathmandu, Nepal:

Central Bureau of Statistics. (2017). Population Density. Retrieved from http://cbs.gov.np/photo_gallery_photo_gallery_photo_gallery_population

Chan, H.-Y., Riffat, S. B., & Zhu, J. (2010). Review of passive solar heating and cooling technologies. *Renewable and Sustainable Energy Reviews, 14*(2), 781-789.

Crawford, W. K. M. (1980). *Convective Heat and Mass Transfer*. New Delhi: McGraw-Hill Publising Co. Ltd.

Department of Hydrology and Meteorology. (2013). *Climate Normals*. Retrieved from Kathmandu, Nepal:

Department of Hydrology and Meteorology. (2015). *Study of Climate and climatic variation over Nepal*. Retrieved from Nepal:

DIY Glass. (2017). 2000X1200X12MM TOUGHENED AND HEAT SOAKED GLASS POOL FENCE / BALUSTRADE PANELS WITH POLISHED EDGES. Retrieved from http://www.diyglass.com.au

Duffie, J. A., & Beckman, W. A. (1991). *Solar Engineering of Thermal Processes*: Wiley.

Fisk, W. J., Rosenfild, Arthur H. (1997). Estimates of Improved Productivity and Health from Better Indoor Environments. *Indoor Air, 7*(3).

Ghoshdastidar, P. S. (2012). *Heat transfer*: Place of publication not identified Oxford University Press.

Himalayan Learning. (2017). Life for Children. Retrieved from http://himalayanlearning.org/

Iqbal, M. (1983). *An Introduction To Solar Radiation*. New York: Elsevier.

Londark Co. (2017). Plastic Clear 6M WIDE POLYTHENE Greenhouse Cover Dust Heavy Duty Sheeting. Retrieved from http://www.ebay.com.au

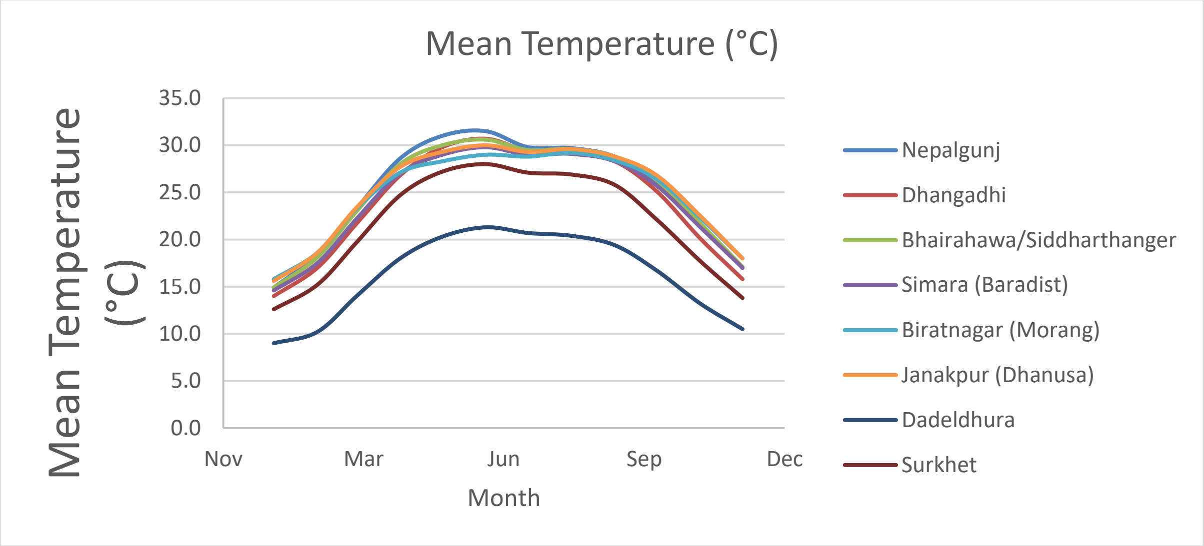
Macgregor, R. K., & Emery, A. F. (1969). Free Convection Through Vertical Plane Layers—Moderate and High Prandtl Number Fluids. *Journal of Heat Transfer, 91*(3), 391.

Matweb. (2017). Material Property Data. Retrieved from http://www.matweb.com
McAdams, W. (1954). *Heat Transmission*. New York: McGraw-Hill.
McFarland, R. D., & Balcomb, J. D. (1979, 1979-01-01). *Effect of design parameter changes on the performance of thermal storage wall passive systems*, United States.
Mendell, M. J., & Heath, G. A. (2005). Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature. *Indoor Air, 15*(1), 27-52.
NASA. (2017). NASA Surface meteorology and Solar Energy: RETScreen Data.
Nepal Electricity Authority. (2016). *A Year in Review-Fiscal Year 2015/2016*. Retrieved from Kathmandu, Nepal: http://www.nea.org.np
Nguyen, A.-T., & Reiter, S. (2014). A climate analysis tool for passive heating and cooling strategies in hot humid climate based on Typical Meteorological Year data sets. *Energy and Buildings, 68, Part C*, 756-763.
Palram. (1997). *Suntuf Trimdeck Premium*. Retrieved from http://www.palram.com.au/palsun
Perspex. (2017). *Perspex Cell Cast Acrylic, Technical Data Sheet*. Retrieved from http://www.perspex.com
Sanusi, A. N. Z., Shao, L., & Ibrahim, N. (2013). Passive ground cooling system for low energy buildings in Malaysia (hot and humid climates). *Renewable Energy, 49*, 193-196.
Sharifi, A., & Yamagata, Y. (2015). Roof ponds as passive heating and cooling systems: A systematic review. *Applied Energy, 160*, 336-357.
Smart Shelter Research. (2016). *Non-Engineed Earthquake Design: 10 Rules of Thumb for Best Practice*.
Tarazi, N. K. (1991). A model of a Trombe wall. *Renewable Energy, 1*(3), 533-541.
The World Bank Group. (2017). Climate Change Knowledge Portal. Retrieved from http://sdwebx.worldbank.org/climateportal/index.cfm?page=country_historical_climate&ThisCCode=IND
Watmuff, J. H., Charters, W. W. S., & Proctor, D. (1977). Solar and wind induced external coefficients - Solar collectors. *Cooperation Mediterraneenne pour l'Energie Solaire*, 56.
World Wearther INformation Service. (2017). Climatological Information. Retrieved from http://worldweather.wmo.int

9. APPENDIX

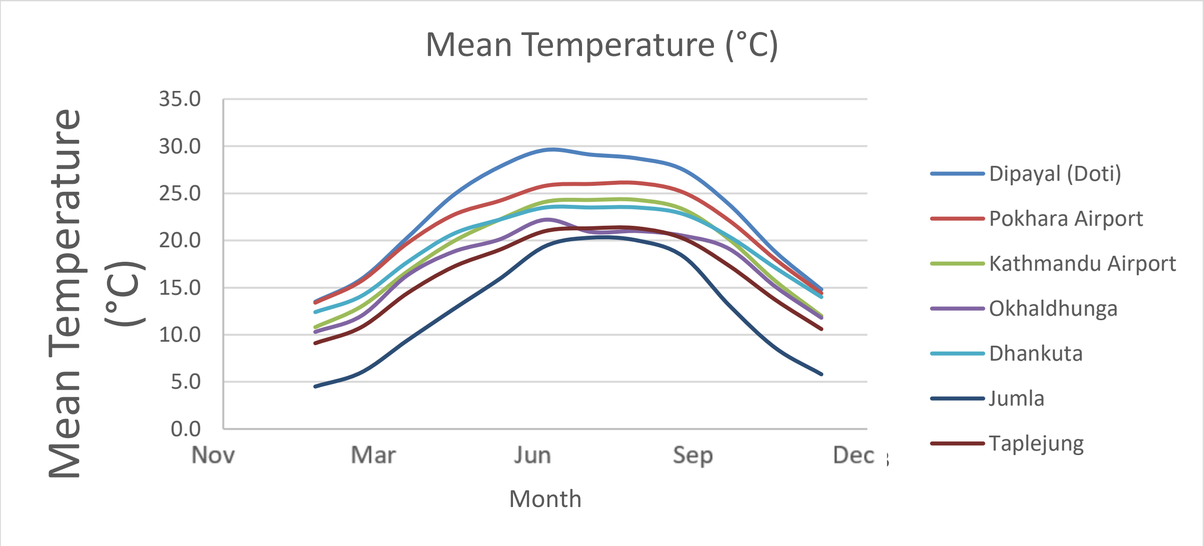
9.1. Meteorological Climate Normal Data, 1981-2010 for Tarai and Siwalik regions

(data obtained from Department of Hydrology and Meteorology, 2013)

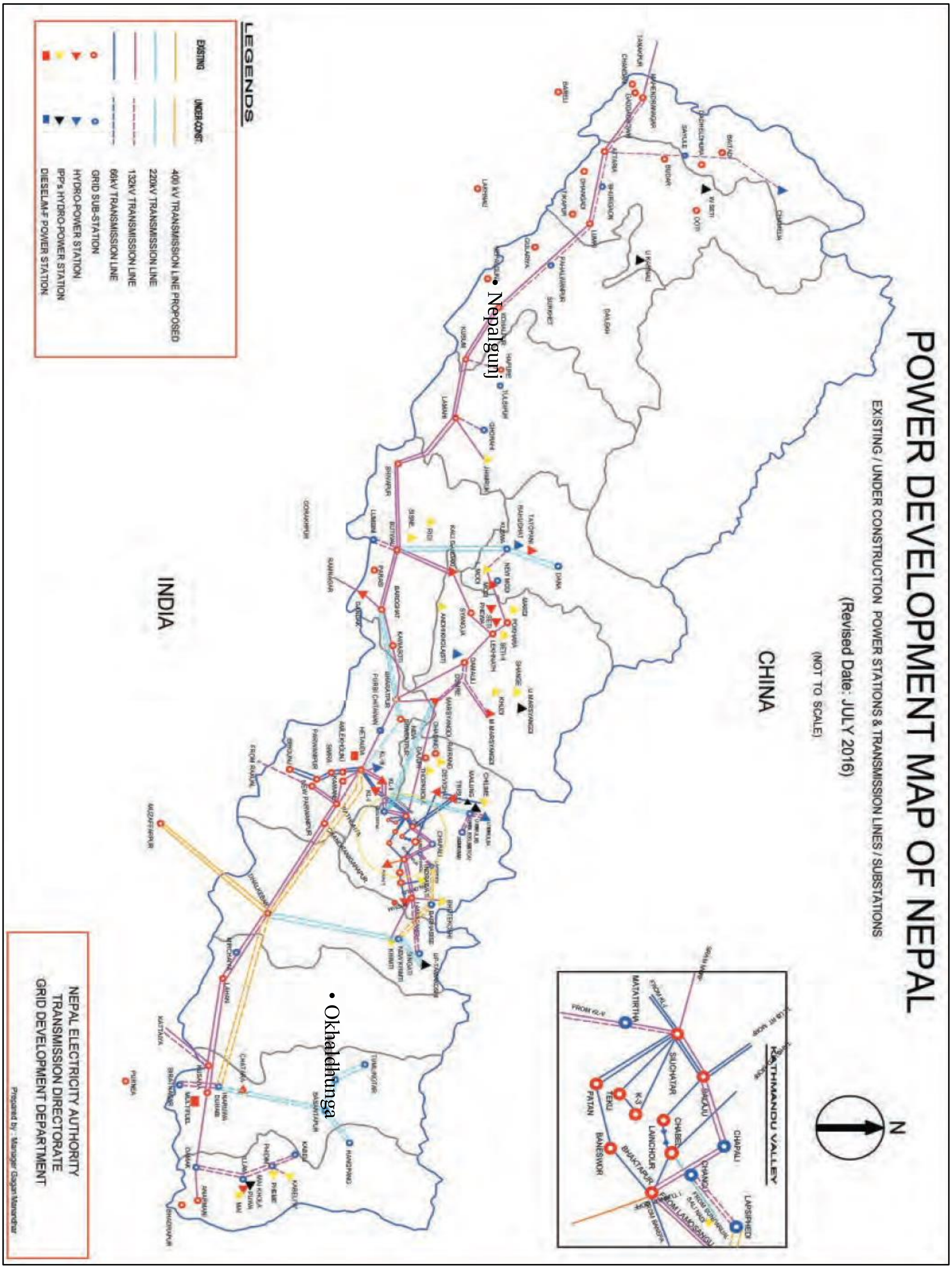


9.2. Meteorological Climate Normal Data, 1981-2010 for Middle and High Mountain Regions

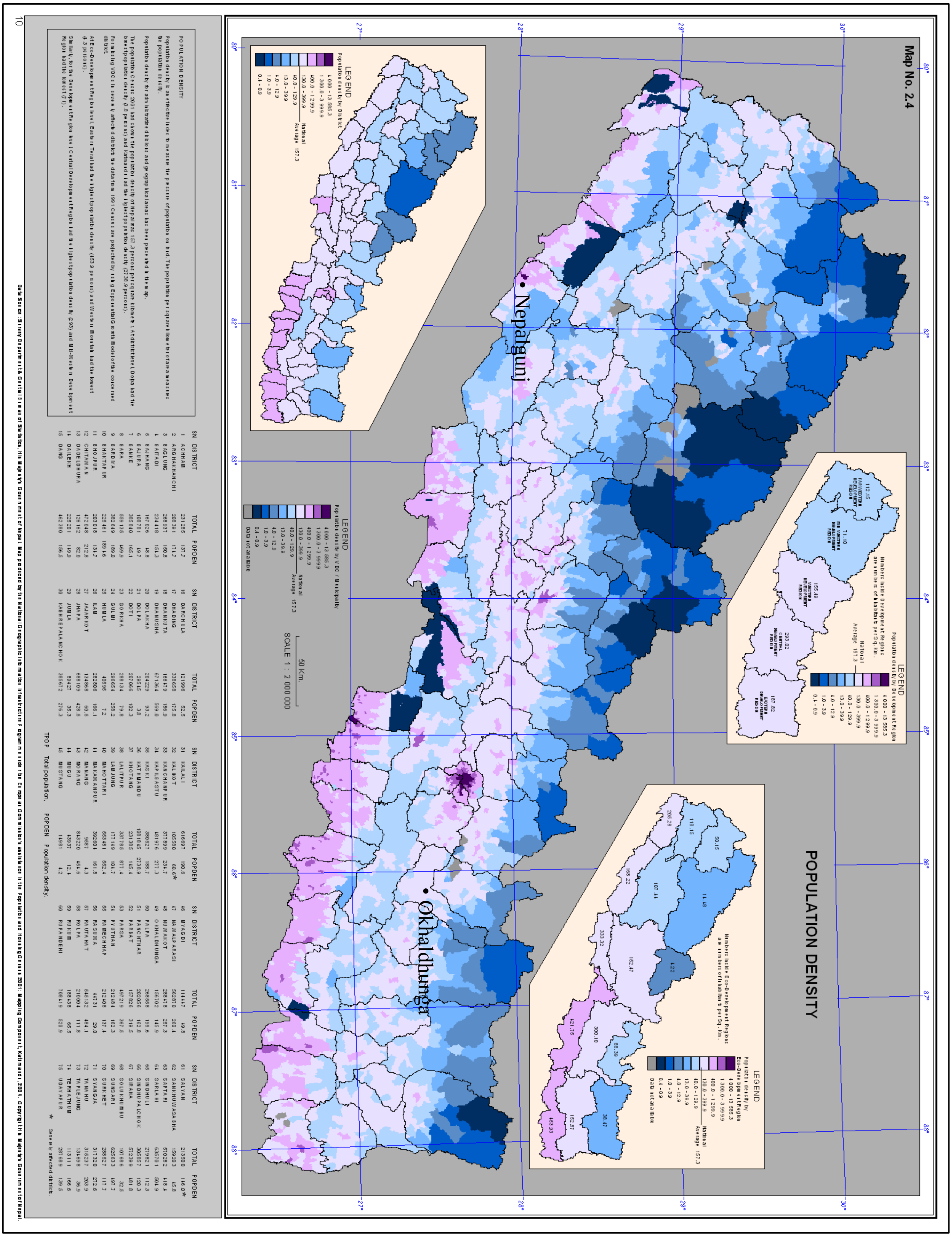
(data obtained from Department of Hydrology and Meteorology, 2013)



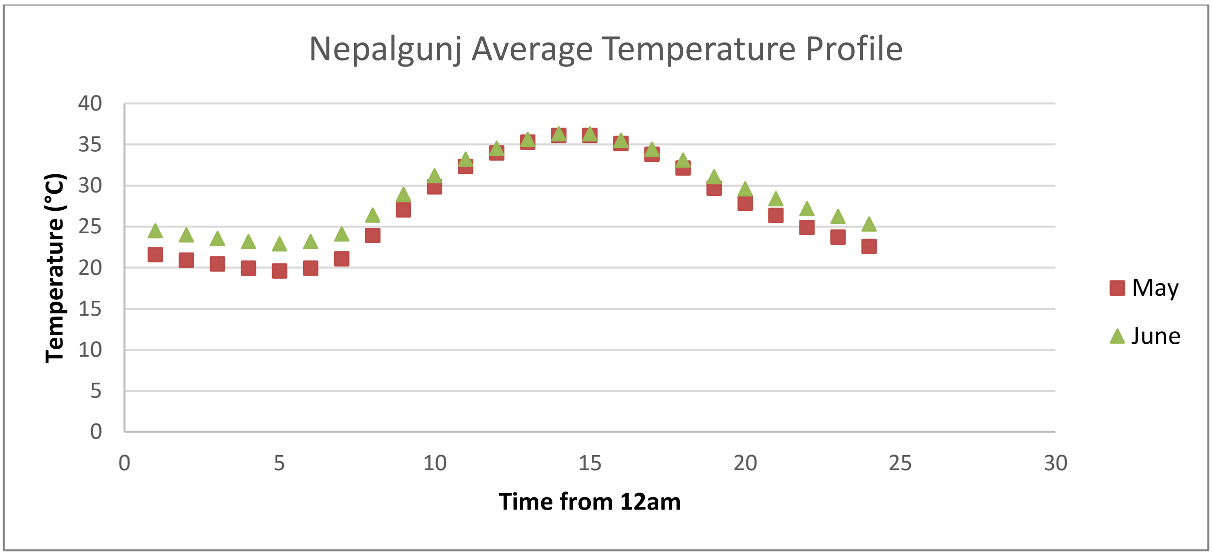
9.3. Nepalese Power Grid (Nepal Electricity Authority, 2016)



9.4. Nepalese Population Density (Central Bureau of Statistics, 2017)



9.5. Nepalgunj Temperature Profile Based on ASHRAE (2013)



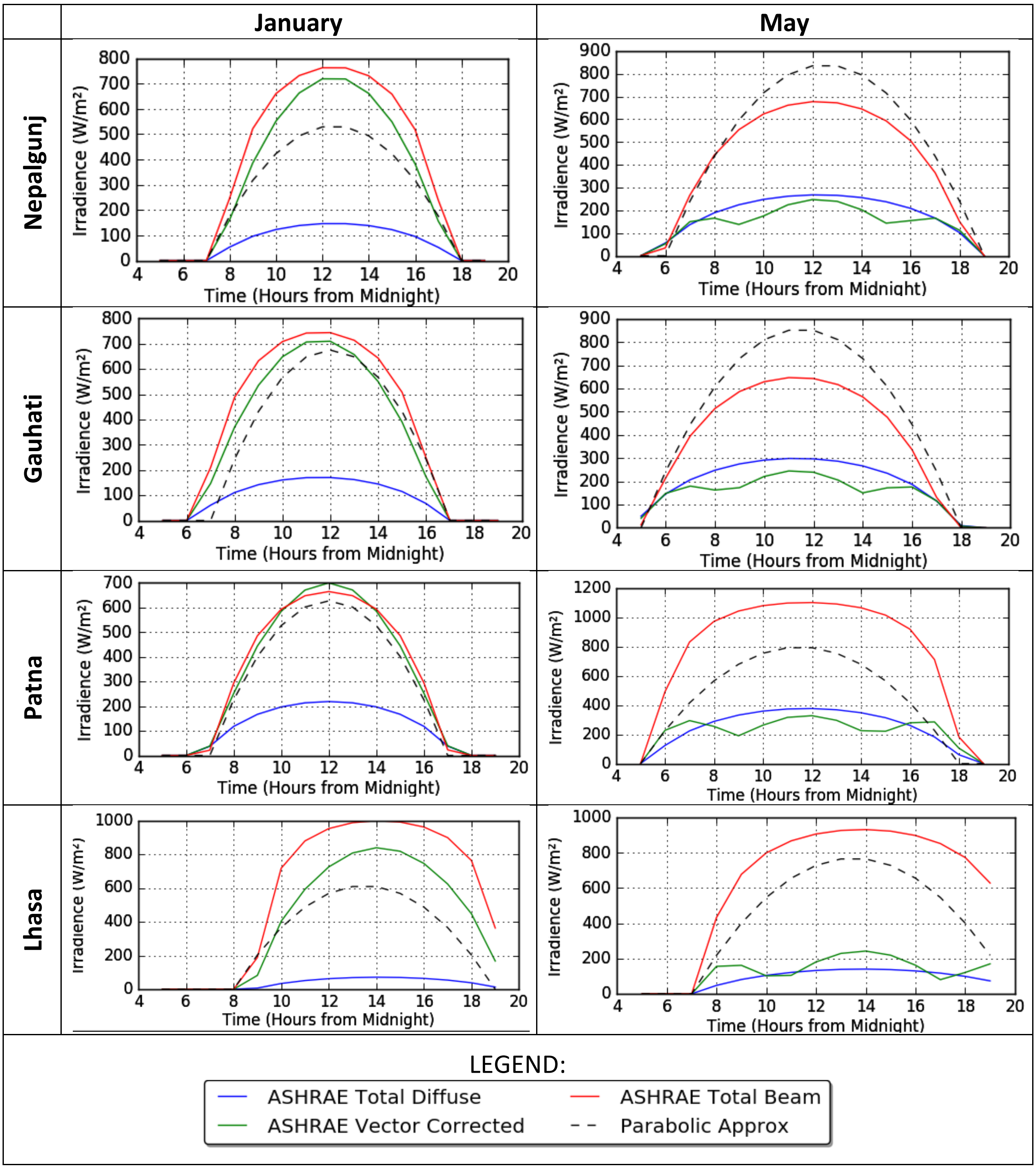
9.6. Comfort Limits

Location	Month	Humidity (%R.H)	Min (°C)	Max (°C)
Nepalgunj	January	44.0	20.5	27
	May	56.3	19.5	27
Okhaldhunga	January	47.7	20.5	27
	May	77.0	19.5	22
Gauhati	January	46.7	20.5	27
	May	66.9	19.5	24
Patna	January	47.4	20.5	27
	May	64.6	19.5	24
Lhasa	January	37.0	21.0	27.5
	May	55.9	19.5	27

9.7. ‘Non-Engineered’ Principles for Building Constructions

1. Don’t Build on Slopes; stay 3 meters from edges
2. Simple Symmetric Shapes
3. Separate Building Volumes; make gap or corridor
4. Maximum Dimensions for Width and Length
    a. Maximum Width versus Length Ratio is 1:3
    b. Maximum Free Span is 6 meters
    c. Maximum distance between Confined Masonry columns is 4 meters
5. Maximum Height
    a. Bricks and blocks: Maximum height = 3.0 meter
    b. Rubble stones: Maximum height = 2.8 meter
6. Horizontal Reinforcements; at all construction types!!
    a. Minimum 2 beams for minor to medium earthquake zones
        -Plinth beam
        -Lintel Beam
    b. Preferably 5 beams for heavy earthquake zones
        -Plinth beam
        -Sill beam
        (Smart Shelter Research, 2016)-In-Between Stitches
        -Lintel Beam
        -Top Beam
7. Vertical Steel; at thin walled structures
    a. YES at all Brick and Block Masonry:
        -3 bars at corners
        -4 bars at T-sections
        -next to all doors and windows
    b. NO vertical reinforcements at thick and massive walls:
        -Good bonding between stones
        -Cement mortar
8. Maximum Dimensions of Openings
    a. Not exceeding 50% of wall surface
    b. Minimum 60 cm from corners and t-sections
    c. Doors must open to the outside
9. Regular Vertical Load Path, no Soft Storey
10. No Loose Elements

9.8. Irradiance Comparison Graphs



9.9. Comparing Resistivity of Components

From inner to outer cover surface of 3mm acrylic: d – component thickness – component thermal conductivity (0.2w/m•K)

$$R_{ci-co} = \frac{1}{h} = \frac{d}{k} = \frac{0.003}{0.2} = 1.5\times10^{-2}$$

From cover to atmosphere with V – wind speed velocity (assumed 0)

$$R_{c-a} = \frac{1}{h_{c,c-a}} = \frac{1}{2.8 + 3.0V = 2.8 + 3.0\times0} = 3.57\times10^{-1}$$

$$R_{ci-co} = 4.2\%\times R_{c-a}$$

9.10. Solar Irradiance Calculation

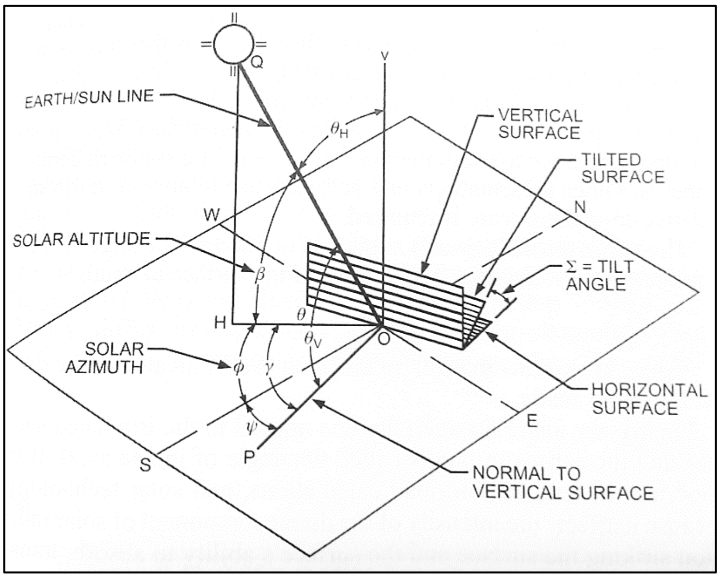


Figure 30, Solar Angles for Vertical and Horizontal Surfaces (ASHRAE, 2013, CH 14.9)

$$E_{t,b} = E_b\cos\theta \tag{38}$$

$$E_{t,d} = E_d Y \tag{39}$$

γ - surface solar azimuth angle (°)
θ - incident angle

$$Y = \max(0.45, 0.55 + 0.437cos\theta + 0.313cos^2\theta) \qquad , for\ vertical\ surfaces$$

θ - incident angle

$$cos\theta = cos\beta cos\gamma$$

$$\gamma = \phi - \psi$$

The beam and diffuse intensities are determined as follows:

$$E_b = E_0 \exp(-\tau_b m^{ab})$$

$$E_d = E_0 \exp(-\tau_d m^{ab})$$

τ_b and τ_d - pseudo beam and diffuse optical depths (respectively) as tabulated

E_0 - Extra-terrestrial normal irradiance

$$E_0 = E_{sc}\left\{1 + 0.033 \cos\left(360° \frac{n-3}{365}\right)\right\}$$

n - day of the year (n=32 for February 1)

E_{sc} is the solar constant, commonly 1367 W/m^2 (Iqbal, 1983)

m - Air mass

ab and ad – Beam and diffuse air mass exponents (respectively) dependent on the optical depths

$$ab = 1.454 - 0.406\tau_b - 0.268\tau_d + 0.021\tau_b\tau_d$$

$$ad = 0.507 + 0.205\tau_b - 0.080\tau_d - 0.190\tau_b\tau_d$$

$$m = 1/[sin\beta + 0.50572(6.07995 + \beta]^{-1.6364}$$

φ - Azimuth angle

$$sin\phi = sinHcos\delta/cos\beta$$

$$cos\phi = (cosHcos\delta sinL - sin\delta cosL)/cos\beta$$

β - solar altitude

$$sin\beta = cosLcos\delta cosH + sinLsin\delta$$

H - hour angle

$$H = 15(AST - 12)$$

δ - solar declination

$$\delta = 23.45 \sin\left(360° \frac{n + 284}{365}\right)$$

AST - Apparent solar time

$$AST = LST + \frac{ET}{60} + (LON - LSM)/15$$

LST – Local standard time, (during daylight savings, LST is the daylight savings time DST -1)

LSM – Longitude of local standard time meridian, °E of Greenwich (neg in west hemisphere)

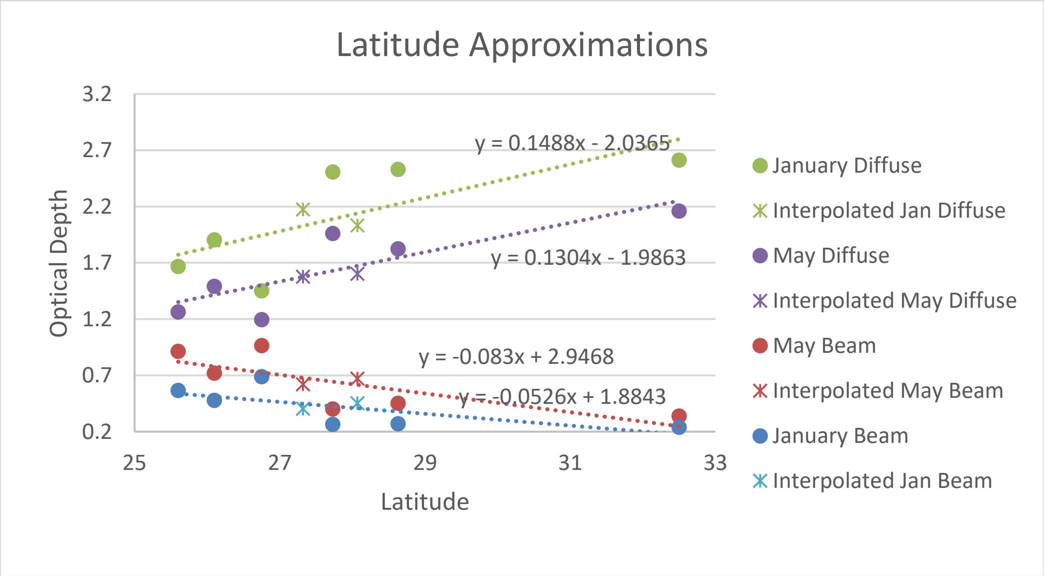
LON – Longitude of Location

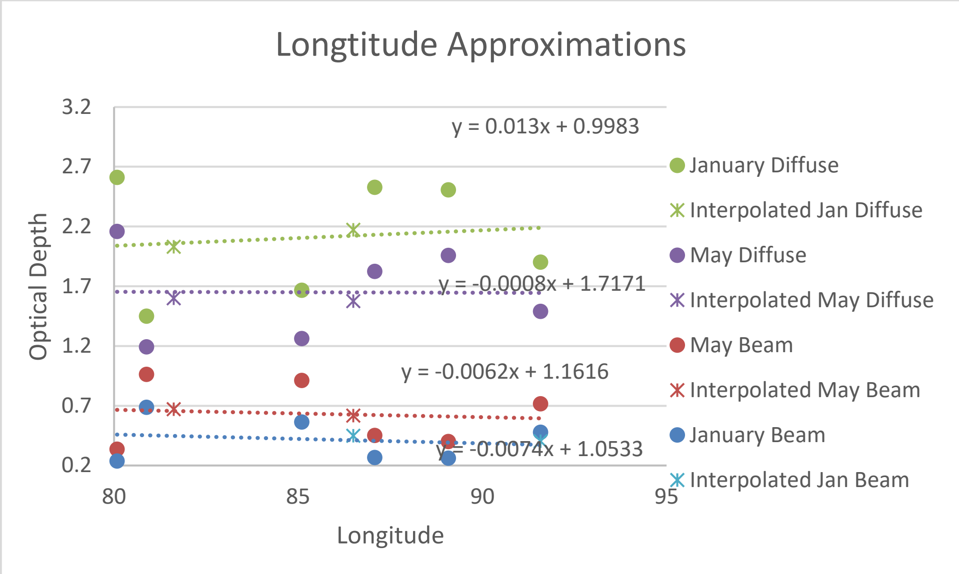
ET – Equation of time

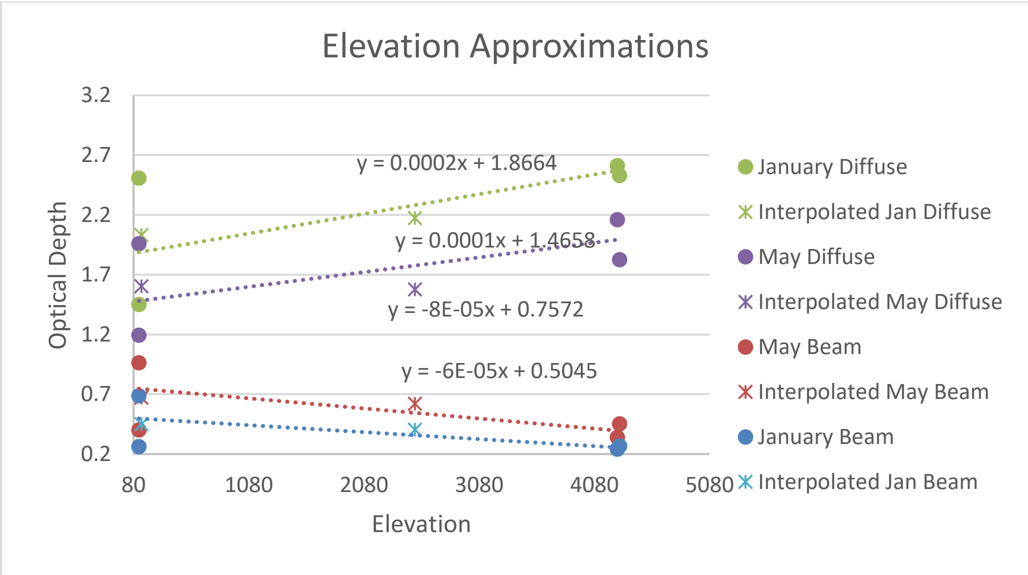
$$ET = 2.2918(0.0075 + 0.1868cos\Gamma - 3.2077sin\Gamma - 1.4615cos2\Gamma - 4.089sin2\Gamma)$$

$$\Gamma = 360° \frac{n - 1}{365}$$

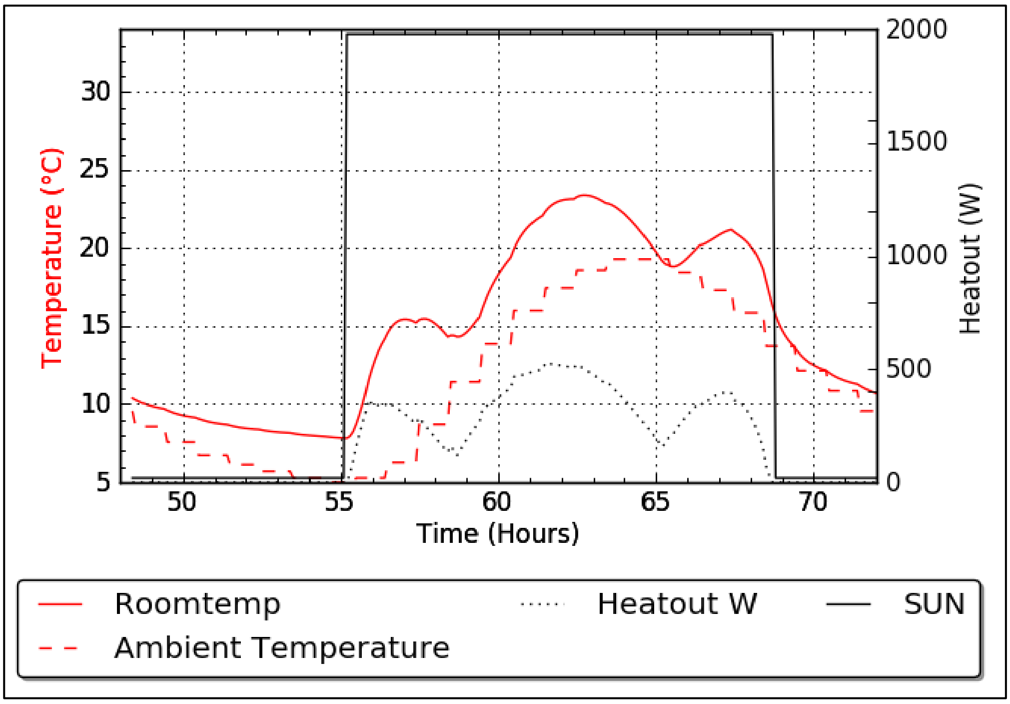
9.11. Optical Depth Interpolation Graphs




Longtitude Approximations
Optical Depth
Longitude
3.2
2.7
2.2
1.7
1.2
0.7
0.2
80
85
90
95
y = 0.013x + 0.9983
y = -0.0008x + 1.7171
y = -0.0062x + 1.1616
y = -0.0074x + 1.0533
January Diffuse
Interpolated Jan Diffuse
May Diffuse
Interpolated May Diffuse
May Beam
Interpolated May Beam
January Beam
Interpolated Jan Beam

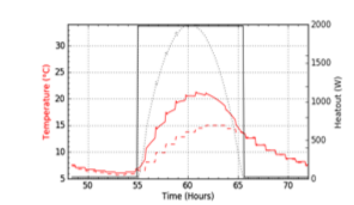
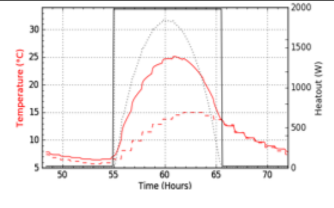
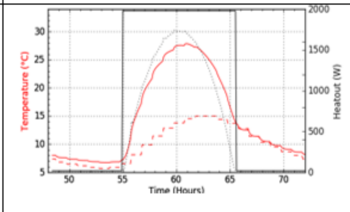
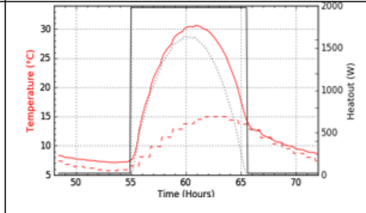
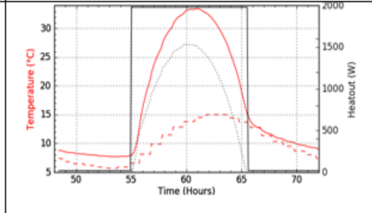
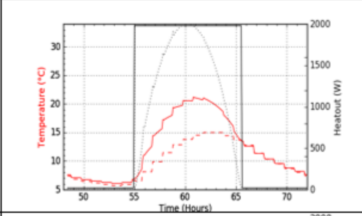
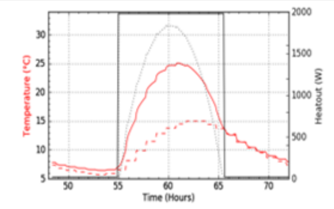
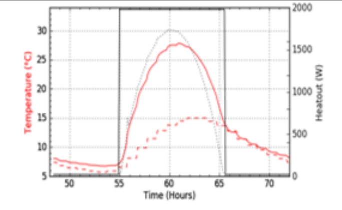
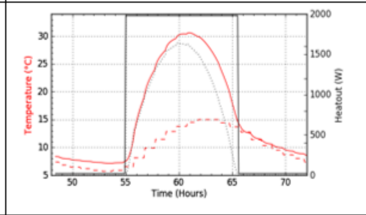
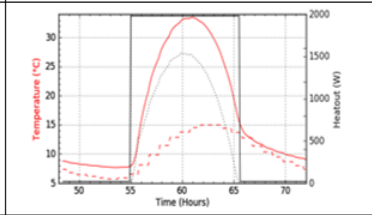
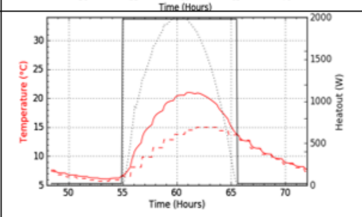
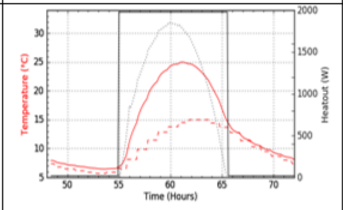
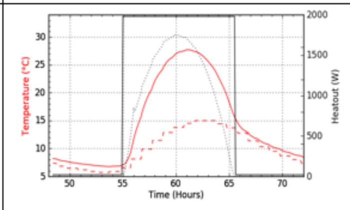
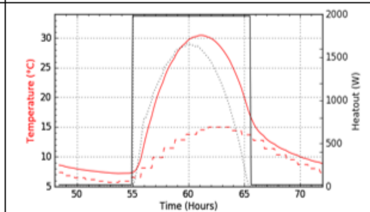
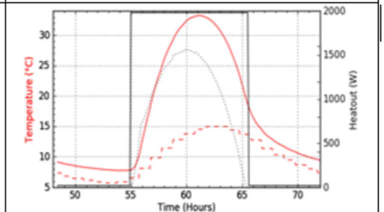
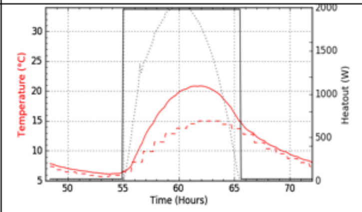
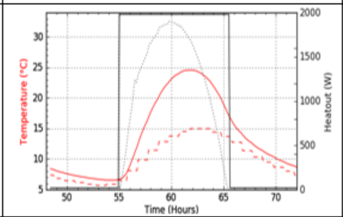
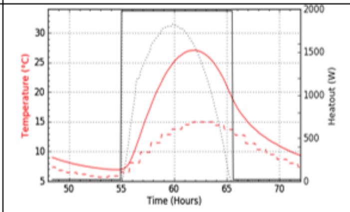
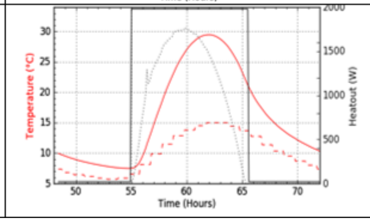
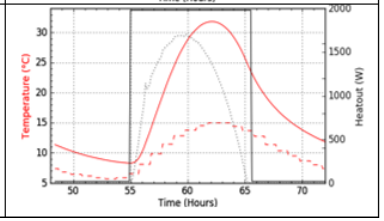

Elevation Approximations
Optical Depth
Elevation
3.2
2.7
2.2
1.7
1.2
0.7
0.2
80
1080
2080
3080
4080
5080
y = 0.0002x + 1.8664
y = 0.0001x + 1.4658
y = -8E-05x + 0.7572
y = -6E-05x + 0.5045
January Diffuse
Interpolated Jan Diffuse
May Diffuse
Interpolated May Diffuse
May Beam
Interpolated May Beam
January Beam
Interpolated Jan Beam

9.12. Heating Lhasa in May



r = 0.05 (K/W)	$C_{p,r}$ = 105 (KJ/K)	ε_c = 0.75	ε_w = 0.90
ρ_w = 2400	$C_{p,w}$ = 900 (J/kg·K)	w_a = 0.90	k_w = 0.7
Orientation South	Wall length 5m		

9.13. Room Characteristic Dependency Plots for Okhaldhunga in January

R (K/W) / Cp (x10^5)	0.004	0.008	0.012	0.018	0.028
0.9 (5.5x5.5m)					
1.05 (6x6m)					
2.5 (9x9m)					
6.7 (15x15m)					

r = 0.008 (K/W)	$C_{p,r}$ = 105 (KJ/K)	ε_c = 0.75	ε_w = 0.90
ρ_w = 2400	$C_{p,w}$ = 900 (J/kg·K)	w_a = 0.90	k_w = 0.7
Orientation South			

9.14. Python Script

Trombe4.py

```
#Trombe4
"""
This module takes the Equations from Tarazi paper to calculate outputs
currently building funcitons
SI UNITS, Temperatures in K
"""
#print("start")
#importing
import math

def Airprop(T):

    """Temperature in K
    Returns Cp in J/kgK
    rho in mg/m3
    vis m2/s
    k in W/mK
    Pr
    """
    #print(T)
    if T < 250:
        print("Temperature Below Tab range",T)
    if T <= 300 and T >= 250:
        fraction =(T-250)/(300-250)
        Cp = 1006+fraction*(1007-1006)
        rho = 1.3947+fraction*(1.1614-1.3947)
        vis = (11.44+fraction*(15.89-11.44)) *1E-6
        k = (22.3+fraction*(26.3-22.3)) *1E-3
        Pr = 0.720+fraction*(0.707-0.720)
        beta = (2.884+fraction*(2.881-2.884))*1E-3
    else:
        fraction = (T-300)/(350-300)
        Cp = 1007+fraction*(1009-1007)
        rho = 1.1614+fraction*(0.9950-1.1614)
        vis = (15.89+fraction*(20.92-15.89)) *1E-6
        k = (26.3+fraction*(30.3-26.3)) *1E-3
        Pr = 0.707+fraction*(0.700-0.707)
        beta = (2.881+fraction*(2.880-2.881))*1E-3
        if T > 350: print("temp Above Tab Range")
    return Cp, rho, vis, k, Pr, beta

def UBcalc(wt,wk,hc):
    Rwowi = wt/wk
    Rcwir = 1/hc
    UB = 1/(Rwowi+Rcwir)
    return UB


def Ufcalc(vel,we,Tw,Ta,Tfm,sig,ce,hcwog):
    Tg = Tw + 2*(Tw-Tfm)
    hcga = 2.8+3*vel
    hrwog = (sig*(Tw+Tg)*(Tw**2+Tg**2))/((1/we)+(1/ce)-1)
    hrga = sig*ce*(Tg+Ta)*(Tg**2+Ta**2)
    Rwog = 1/(hcwog+hrwog)
    Rga = 1/(hcga+hrga)
    Uf = 1/(Rwog+Rga)
    return Uf

def Racalc(Pr,g,beta,Ti,To,D,vis):
    """Calculates the rayleigh number"""
    #print(Ti,To)
    Num = Pr*g*beta*(Ti-To)*D**3
```

```
    #print(Num)
    RaD = Num/(vis**2)
    #print(Ras)
    return RaD

def htc(g,wl,vis,k,Pr,Ti,To,D,beta):
    """
    RETURNS LAM OR TURBLENT HEAT TRANSFER COEFF in enclosed space
    AND type of flow, LAM OR TURB
    """
    HL = wl/D
    Ras = Racalc(Pr,g,beta,Ti,To,D,vis)
    if Ras<0: None#print("Ras negitive",Ras)

    if Ras > 1E4 and Ras <= 1E6:
        Nus = 0.42*pow(Ras,1/4)*pow(Pr,0.012)*pow(HL,-0.3)
        LT = "Turbulent"
    elif Ras > 1E6 and Ras < 1E9:
        Nus = 0.046*pow(Ras,1/3)
        LT = "Turbulent"
    elif Ras < 1E13:
        Nus = 0.18*pow((Pr*Ras)/(0.2+Pr),0.29)*pow(HL,-0.13)
        LT = "HIGH RAYLEIGH"
    else: print("Rayleigh out of range",Ras,Ti,To)
    h = Nus*k/D
    #print("HTCVALS",h,g,wl,vis,k,Pr,Ti,To,D,beta)
    return h, LT

def hccalc(Pr,g,beta,Twi,Tr,vis,wl,k):
    """
    Heat transfer coefficient from wall to open space
    based on L - height of wall
    Tr - Room temp
    Twi - Wall temp (inner)
    """
    RaL = Racalc(Pr,g,beta,Twi,Tr,wl,vis)
    #print("RaL",RaL)
    if RaL < 0: RaL = -RaL
    if RaL < 10**4 or RaL > 10**13:print("WARNING- Ra out of range",RaL)
    if RaL <= 10*9:
        NuL = 0.59*pow(RaL,1/4)
        LT = "Laminar"
    else:
        NuL = 0.1*pow(RaL,1/3)
        LT = "Turbulent"
    h = NuL*k/wl
    return h, LT

def Fdashcalc(h,Ufe,Ub):
    Num = h*(2*h+Ufe+Ub)
    Denom = 2*(h+Ufe)*(h+Ub)
    Fdash = Num/Denom
    return Fdash

def Vcalc(g,wl,Ag,Av,Tfm,Tr):
    Pleft = (2*g*wl)/(8*pow(Ag/Av,2)+2)
    Pright = (Tfm-Tr)/Tfm
    if Pright > 0: V = math.sqrt(Pleft*Pright)
    else: V = 0 #Noflow if negitive gradient
    return V

def Frcalc(mdot,Cp,Ac,Ufe,Ub,Fdash):
    if mdot <= 0: return 0
    power = (-Ac*Fdash*(Ufe+Ub))/(mdot*Cp)
    left = 1
    Fr = ((mdot*Cp/(Ufe+Ub))/Ac)*(left-math.exp(power))
    return Fr
```

```python

    def Qcalc(Ac,Fr,S,Ufe,Ub,Tr,Tin,Ta):
        """ S = ct*wa*I"""
        Q = Ac*Fr*(S-Ufe*(Tin-Ta)-Ub*(Tin-Tr))
        return Q

    def Twcalc(Tin,Q,Ac,Ufe,Ub,Fr):
        if Fr == 0: return Tin
        change = (Q*(1-Fr))/(Ac*Fr*(Ufe+Ub))
        Tw = Tin + change
        return Tw

    def Tfmcalc(Tin,Q,Ac,Ufe,Ub,Fr,Fdash):
        if Fr == 0: return Tin
        change = (Q*(1-Fr/Fdash))/(Ac*Fr*(Ufe+Ub))
        Tfm = Tin+change
        return Tfm

    def Tocalc(Tin,Q,mdot,Cp):
        if mdot == 0: return Tin
        To = Tin + Q/(mdot*Cp)
        return To

    def Irradpara(DSR, DH, t):
        """
        calculates the clear sky radiation
        approximating parabolic curve
        given time from sunrise t, daylight hours DH,  daily irradence DSR #Wh/m2/d
        depends on ....
        returns #w/m2
        """
        if t<0 or t>DH:
            print("Presunrise")
            return 0
        det = -DH**4/6
        A = (DH*DSR)/det
        B = (-DH**2*DSR)/det
        #print(A,B,det)
        Irrad = A*t**2+B*t
        print(Irrad)
        if Irrad < 0: Irrad = 0
        return Irrad    # do not return a negitive value

    def hverwall(beta,g,Tw,Tair,L,k,vis,Pr):
        #duplicate unused
        """
        Calculates heat transfer coefficient for a vertical plate of temperate Tw
        and free stream air temp of tair in K, heat transf k, viscos vis
        Characteristic length L (m)
        """
        Ra = Racalc(Pr,g,beta,Tw,Tair,L,vis)
        #print(Pr,g,beta,Tw,Tair,L,vis,'Ra=',Ra)
        if Ra < 1E4: print("Ra too small", Ra)
        elif Ra > 1E13: print("Ra too large", Ra)
        elif Ra < 1E9: Nu = 0.59*pow(Ra,1/4)
        else: Nu = 0.1*pow(Ra,1/3)
        h = (Nu*k)/L
        return h
```

ASHRAE2.py

```python
#ASHRAE2
"""
Calculates an irradiance value dependent on:
location specific data
longitude
latitude
LSM = Longitude of local standard time mer, East of Greenwich
LON = Longitude of site
L = Local latitude

AND time/date:
n = day of the year
LST = Local standard time

AND geometry/orientation of receiver:

Theta = incident Angle
Beta = Solar Altitude
Phi = Azimuth angle
Delta = solardeclination
SSA = Surface solar azimuth angle
SA = Surface Azimuth

Eb,Ed,Er = Beam, Direct, Reflectiveirradience intensities
Eo = Extraterrestiral normal irradiance
Esc = Solar Constant 1367 (W/m2)
ab, ad = air mass exponents
taub, taud = beam and diffuse optical depths

AST = Apparent solar time
ET - Equation of time

"""
import math

### NEED TO CHECK WHAT IS IN RAD AND WHAT IS IN DEGREES

#because everything is in degrees
def cosd(ANGLE):
    return math.cos(math.radians(ANGLE))
def sind(ANGLE):
    return math.sin(math.radians(ANGLE))
def acosd(FRAC):
    return math.degrees(math.acos(FRAC))
def asind(FRAC):
    return math.degrees(math.asin(FRAC))

def TotIrrad(SA,n,LSM,LST,LON,L,taub,taud,Esc=1367):
    """
    Returns
    Et
    Beta
    SSA
    """
    Gamma = 360*(n-1)/365
    ET = 2.2918*(0.0075+0.1868*cosd(Gamma)-3.2077*sind(Gamma)
                 -1.4615*cosd(2*Gamma)-4.089*sind(2*Gamma))
    AST = LST+(ET/60)+(LON-LSM)/15
    H = 15*(AST-12)
    Delta = 23.45*sind(360*(n+284)/365)
    Betaleft = cosd(L)*cosd(Delta)*cosd(H)
    Betaright = sind(L)*sind(Delta)
    Beta = asind(Betaleft+Betaright)
    Phi1 = asind((sind(H)*cosd(Delta))/cosd(Beta))
```

```
    Phi11 = asind(sind(H)*cosd(Delta)/cosd(Beta))
    Phi2left = cosd(H)*cosd(Delta)*sind(L)
    Phi2right = sind(Delta)*cosd(L)
    Phi2 = acosd((Phi2left-Phi2right)/cosd(Beta))
    Phi22 = acosd((cosd(H)*cosd(Delta)*sind(L)-sind(Delta)*cosd(L))/cosd(Beta))
    #print(LST,"Phi1,Phi2=",Phi1,Phi11,Phi2,Phi22)
    #Check
    check = abs(Phi1)-abs(Phi2)
    if check > 0.01: print("Phi values disagree by...", check)
    Phi = Phi1
    SSA = Phi - SA
    Theta = acosd(cosd(Beta)*cosd(SSA))
    #print(Theta)
    ab = 1.454-0.406*taub-0.268*taud+0.021*taub*taud
    ad = 0.507+0.205*taub-0.080*taud-0.190*taub*taud
    #print("ab,ad",ab,ad)
    Eo = Esc*(1+0.033*cosd(360*(n-3)/365))
    if Beta<0:
        Eb = 0
        Etb = 0
        Ed = 0
    else:
        m = 1/(sind(Beta)+0.50572*pow((6.07995+Beta),-1.6364))
        #print("m=",m,"Beta=",Beta)
        Eb = Eo*math.exp(-taub*pow(m,ab))
        Ed = Eo*math.exp(-taud*pow(m,ad))
        Etb = Eb*cosd(Theta)
    Y = max(0.45,0.55+0.437*cosd(Theta)+0.313*cosd(Theta)**2)
    Etd = Ed*Y
    Etr = 0 #for completeness
    #print("Eb,Ed,Etb,Etd",Eb,Ed,Etb,Etd)
    Et = Etb+Etd+Etr
    return Et, Beta, SSA, Eb, Ed, AST

def ncalc(MON,DAY):
        """ Calculates the day of the year
        assuming not a leap year"""
        n = 0
        DIM = [31,28,31,30,31,30,31,31,30,31,30,31]
        for i in range(0,MON-1):
            n = n + DIM[i]
        n = n + DAY
        while DAY > DIM[MON-1]:
            print(MON-1)
            DAY = DAY- DIM[MON-1]
            MON = MON+1
        return n, MON, DAY

    FDTR = [0.82,0.88,0.92,0.95,0.98,1.00,0.98,0.91,0.74,
            0.55,0.38,0.23,0.13,0.05,0.00,0.00,0.06,
            0.14,0.24,0.39,0.50,0.59,0.68,0.75]

    def tempgrad(AST,Tmax,Tmin):
        """
        Returns the ambient temperature at a time of day accrding to the fraction

        daily distribution of ASHRAE and Max and Min daily temperatures
        """
        Tdiff = Tmax-Tmin
        i = round(AST)%24
        #print(i)
        Ta = Tmax-FDTR[i]*Tdiff
        return Ta
```

SimulationTransient7.py

```python
#SimulationTransient7

"""
Takes funcitons built in Throme4 and runs simulation procedure
"""
print("start")
#importing
from Trombe4 import *
from ASHRAE2 import *
import numpy as np


#initial conditions
#constants
kelvin = 273.15     #kelvin
g = 9.81            #gravity (m/s2)
sig = 5.6704E-8     #stephan-boltzmann (W.m-2.k-4)

#Building conditions

Rr = 0.008          #room thermal resistence (K/W)
MCp = 1.05E5           #Room thermal capacity (j/K)
wl = 2.5            #wall height (m)
wlen = 5            #wall length(m)
D = 0.1             #Distance between wall and glazing (m)
cn = 1              #number of covers
we = 0.90           #wall emissivity
rhow =  2400        #wall density (kg/m3)
Cpw = 900          #heat capacity of wall (J/kg K)
ce = 0.75           #cover emissivity
ct = 0.8            #cover transmissivity
wk = 0.7            #wall conductivity (w/m.k)
wa = 0.90           #wall absorptivity alpha
wt = 0.3            #wall thickness (m)
UAe = 0             #UAe product for edge
PVA = 0.045         #Percentage Vent Area


#Environ conditions
vel = 0             #wind velocity (m/s)
Ambtemp = 20      #ambient temperature deg celcius
Intemp = 10         #starting indoor temperature deg Celc
#I = 420             #w/m2 #Irradpara(DSR,DH,t[-1])

DSR = 5080          #daily solar radiation (Wh/m2/d)
DH = 12             #daylight hours (h)

#Irradience Conditions
if 0:
    """Location Nepalgunj"""
    SA = math.radians(0) #south facing
    Day = 21
    Month = 5   #May
    LSM = 86.33 #Local standard time meridian Longitude
    LON = 81.62 #Longitude of site
    L = 28.07   #Latitude of site
    taub = 0.673     #optical depth beam
    taud = 1.602     #optical depth diffuse
    Tmax = 37.4 + kelvin
    Tmin = 24.6 + kelvin
    vel = 3.9

if 0:
    """Location Nepalgunj"""
```

```
    SA = math.radians(0) #south facing
    Day = 21
    Month = 1   #January
    LSM = 86.33 #Local standard time meridian Longitude
    LON = 81.62 #Longitude of site
    L = 28.07   #Latitude of site
    taub = 0.451     #optical depth beam
    taud = 2.032     #optical depth diffuse
    Tmax = 20.9 + kelvin
    Tmin = 9 + kelvin
    vel = 3.4

if 1:
    """Location Okhaldhunga"""
    SA = math.radians(0) #south facing
    Day = 21
    Month = 1   #January
    LSM = 86.33 #Local standard time meridian Longitude
    LON = 86.50 #Longitude of site
    L = 27.32   #Latitude of site
    taub = 0.405     #optical depth beam
    taud = 2.174     #optical depth diffuse
    Tmax = 15 + kelvin
    Tmin = 5.7 + kelvin
    vel = 4.3

if 0:
    """Location Okhaldhunga"""
    SA = math.radians(0) #south facing
    Day = 21
    Month = 5   #May
    LSM = 86.33 #Local standard time meridian Longitude
    LON = 86.50 #Longitude of site
    L = 27.32   #Latitude of site
    taub = 0.620     #optical depth beam
    taud = 1.576     #optical depth diffuse
    Tmax = 24.6 + kelvin
    Tmin = 15.5 + kelvin
    vel = 4.1

Ac = wl * wlen * (1-
PVA)          #collector area (m2) should account for vents
Ag = wlen * D         #Air gap cross sectional area (m2)
Av = wl*wlen*PVA        #Vent area (m2)
Tr = Intemp + kelvin     #change to kelvin
Ta = Ambtemp + kelvin #change to kelvin

seg = 15     #wall segements for h calc
Two = 10+Tr####
Twi = None



#solver
def Solver(D=D,Intemp=Intemp,Two=Two,Twi=Twi,LST=12,dadd=0,
           Month=Month,Day=Day):
    #Tfm = 20+Tr ##CHECK DEPENDANCES OF THESE
    if Twi == None:Twi = Two
    To = 2*(Two-Tr)+Tr-1####
    Tfm = (To+Tr)/2
    j = 1
    n, Month,Day = ncalc(Month,Day+dadd) #calculate day of year
    I, Beta, SSA, Eb, Ed, AST  = TotIrrad(SA,n,LSM,LST,LON,L,taub,taud)
    Ta = tempgrad(AST, Tmax, Tmin)
    while True:
        #Detemining air gap h value
        hlist = []
```

```
            for i in range(0,seg+1):
                """
                Linearly extrapolates the film temperatures
                across the wall surface for find wall to glazing
                heat transfer coefficient
                """
                Tf = (i/seg)*(To-Tr)+Tr
                Tw1= (i/seg)*2*(Two-Tr)+Tr
                #print(To,Tr,Tf)
                print("LST=",LST,"i=",i,"j=",j,"Tf=",Tf,"Tw1=", Tw1,"Tfm=",Tfm,"Tr=",Tr,"To=",To)
                #print(Tf)
                Cp1, rho1, vis1, k1, Pr1 , beta1= Airprop(Tf)
                hnew, HT = htc(g,wl,vis1,k1,Pr1,Tw1,Tf,D,beta1)
                hlist.append(hnew)
            #print("J=",j,"LST",LST,hnew)
            Cp, rho, vis, k, Pr , beta= Airprop(Tfm)
            hcwog = sum(hlist)/len(hlist) ###
            #print("hlist=",hlist)
            hcwir, LT = hccalc(Pr,g,beta,Twi,Tr,vis,wl,k)

            #Loss Coefficients
            Uf = Ufcalc(vel,we,Two,Ta,Tfm,sig,ce,hcwog)
            #print("Uf,vel,Two,Ta,Tfm,hcwog",Uf,vel,Two,Ta,Tfm,hcwog)
            Ue = UAe/Ac
            Ufe = Uf + Ue
            Ub =  UBcalc(wt,wk,hcwir)

            #Prelim Values
            Tin = Tr
            S = ct*wa*I
            V = Vcalc(g,wl,Ag,Av,Tfm,Tr)
            mdot = (rho*V*Ag)
            #print("Mdot",mdot)
            #Effeciency and heat factors
            Fdash = Fdashcalc(hcwog,Ufe,Ub)
            Fr = Frcalc(mdot,Cp,Ac,Ufe,Ub,Fdash)
            #if j < 10 : Fr = 0.2
            Q = Qcalc(Ac,Fr,S,Ufe,Ub,Tr,Tin,Ta)
            #print("After Qcalc, Ac,Fr,S,Ufe,Ub,Tr,Tin,Ta",Qcalc, Ac,Fr,S,Ufe,Ub,Tr,Tin,Ta)
            #New temperatures
            Twnew = Twcalc(Tin,Q,Ac,Ufe,Ub,Fr)
            #print(Twnew)
            Accuracy = abs(Twnew-Two)
            Two = Twnew
            Tfm = Tfmcalc(Tin,Q,Ac,Ufe,Ub,Fr,Fdash)

            To = Tocalc(Tr,Q,mdot,Cp)
            #print("after Tocalc, To, Tr, Q ,mdot", To,Tr,Q,mdot)
            if Accuracy < 0.0001 :
                #print("Q",Q,"To",Fdash,"answer is accurate")
                #print("hc=",hcwog,"Fdash=",Fdash,"Fr=",Fr,"mdot=",mdot,"V=",V,"S=",S,"Ufe=",
                #        Ufe,"Ub=",Ub,"Two",Two,"Tfm",Tfm,"To",To,"Q",Q)
                break               #answer is accurate
            else: j=j+1
        return To, Tfm, Two, Q, mdot, hcwog, Ufe, Ub, I, Ta

    def Wallheat(TS,Tw,Tr,SUN,dt,wt=wt,wk=wk,rhow=rhow,Cpw=Cpw):
        """
        TS = Temperature distributions horizontal Tw to Tn
              time itterations vertical down
        SUN = boolean true or false if there is daylight
        dt = timestep seconds
        Performs an itteration of temperature conduction through a wall
        Returns a new TS and heat transfer Q after 1 hour of interations
```

```
        """
        #if sun = true, don't calc first value
        t = dt
        N1 = len(TS.T)
        TSold = TS[-1]
        wallseg = N1-2
        new = TSold
        dx = wt/(wallseg)
        M = (wk*dt)/(rhow*Cpw*dx**2)
        if SUN == 1: initial = 3
        else: initial = 2
        mid = int(N1/2)#middle value
        low = TSold[mid]
        diff = 0
        new[1]= TW
        while True:
            #TSold = new
            for i in range(initial,N1-1):
                new[i] = M*(TSold[i-1]+TSold[i+1])-(2*M-1)*TSold[i]
            newdiff = abs(low-new[mid])
            if newdiff > diff: diff = newdiff
            #print(new,TSold)
            t = t + dt
            #print("t=%.1f"%(t),"dt=%.1f"%(dt))
            if t > 60**2: break
        return new, diff


    #print("To = %.2f"%(To-kelvin),"Tfm = %.2f"%(Tfm-kelvin),"Tw = %.2f"%(Tw-kelvin),
    #       "Q = %.2f"%(Q),"mdot = %.6f"%(mdot))

    Dlist = [0.01,0.02,0.05,0.08,0.1,0.2]

    """number of segments = wallseg
        number of temperatures = N1"""
    if __name__ == "__main__":
        if 0: #Steady State response analysis
            Outtemp = []
            Heatout = []
            Massflow = []
            Filmtemp = []
            HTC = []
            UBS = []
            for i in Dlist:
                print("i=",i)
                OT,TFM,TW,HO,MDOT,H, UFE, UB, IR, Ta = Solver(D=i)
                Outtemp.append(OT-kelvin)
                Heatout.append(HO)
                Massflow.append(MDOT)
                Filmtemp.append(TFM)
                HTC.append(H)
                UBS.append(UB)

    ###################
        if 1:
            t=1
            Time = [t]
            notimes = 50 #number of itterations in 1 hour
            dt = (60**2/notimes)
            wallseg = 5
            dx = wt/wallseg
            Tr = Intemp+kelvin
            TS = np.zeros((1,wallseg+2))
            #print(TS)
            variance = [0,0]
            #initial Conditions
```

```
        TSnew = [0]###calc later h1
        OT,TFM,TW,HO,MDOT,H, UFE, UB, IR, Ta = Solver(Twi=Twi,LST=t)##Twi
        TroomB = [Tr]
        dadd = 0
        for i in range(0,wallseg):
            #initial temperature setup (guess linear distribution)
            TS1 = TW-i*(TW-Tr)/wallseg
            TSnew.append(TS1)

        while True:   #transient response analysis
            """
            Loops/simulates through several hours using solver() wall hallheat
            """
            wkdx =(wk/(2*dx))
            LST = t % 24 #local standard time
            dadd = int(t/24)
            if len(Time) < 2:
                OT,TFM,TW,HO,MDOT,H, UFE, UB, IR, Ta = Solver(Intemp=Tr-kelvin,LST=LST)
            else:
                Two = TW# TS[-1,-2]
                Twi = TS[-1,-2]
                print ("Twi,Two=",Twi,Two)
                OT,TFM,TW,HO,MDOT,H, UFE, UB, IR, Ta = Solver(Intemp=Tr-kelvin,LST=LST,Twi=Twi,dadd=dadd)
                #print(TW)
            Cp, rho, vis, k, Pr, beta = Airprop(Tr) #room values
            if len(Time)<2:
                T0 = TW
                Tn1 = Tr
                TSnew[0]=T0
                TSnew.append(Tn1)
                Q = 0
                SUN = 0
            else:
                TSold = TS[-1]
                h1 = H
                T0 = (h1*TSold[1]-wkdx*TSold[2])/(h1-wkdx)
                #print(TSold[-2],Tr)
                h2, LT = hccalc(Pr,g,beta,TSold[-2],Tr,vis,wl,k)
                #print("h2=",h2,"LT=",LT)
                Tn1 = TSold[-3]-(h2/wkdx)*(TSold[-2]-Tr)
                #Then start heat transfering
                if IR >0 :###DAYLIGHT HOURS CONDITION
                    SUN = 1
                else: SUN = 0
                TSnew, diff = Wallheat(TS,TW,Tr,SUN,dt)
                variance.append(diff)
                #then append
                TSnew[0]=T0
                TSnew[-1]=Tn1
                Q = h2*Ac*(TSnew[-2]-Tr)
            HO = 0
            if SUN:
                Qtot = Q + HO
            else:
                Qtot = Q
            #if t % 4 == 1:print(Qtot) #print every 4th
            if SUN: TSnew[1]=TW
            TSnew = np.array([TSnew])
            TS = np.r_[TS,TSnew]
            deltaroom = 60**2*(Qtot-(Tr-Ta)/Rr)/MCp
            Tr = TroomB[-1]+deltaroom
            TroomB.append(Tr)
            #print("TS=",TS)
            t = t+1
```

```
                Time.append(t)
                #print("T=",t,",H=",H)
                if t > 3*24:break#notimes: break
            TroomB[:] = [x-kelvin for x in TroomB]

    ###########################

        if 1:
            t=1
            Time = [t]
            notimes = 50 #number of itterations in 1 hour
            dt = (60**2/notimes)
            wallseg = 5
            dx = wt/wallseg
            Tr = Intemp+kelvin
            TS = np.zeros((1,wallseg+2))
            #print(TS)
            variance = [0,0]
            #initial Conditions
            TSnew = [0]###calc later h1
            OT,TFM,TW,HO,MDOT,H, UFE, UB, IR, Ta = Solver(Twi=Twi,LST=t)##Twi
            Troom = [Tr]
            Outtemp = [Tr]
            Heatout = [0]
            Irrad = [0]
            Hs = [0]
            Ambtemp = [282]
            SUNlist = [0]
            dadd = 0
            for i in range(0,wallseg):
                #initial temperature setup (guess linear distribution)
                TS1 = TW-i*(TW-Tr)/wallseg
                TSnew.append(TS1)

            while True:   #transient response analysis
                """
                Loops/simulates through several hours using solver() wall hallheat
                """
                wkdx =(wk/(2*dx))
                LST = t % 24 #local standard time
                dadd = int(t/24)
                if len(Time) < 2:
                    OT,TFM,TW,HO,MDOT,H, UFE, UB, IR, Ta = Solver(Intemp=Tr-kelvin,LST=LST)
                else:
                    Two = TW# TS[-1,-2]
                    Twi = TS[-1,-2]
                    print ("Twi,Two=",Twi,Two)
                    OT,TFM,TW,HO,MDOT,H, UFE, UB, IR, Ta = Solver(Intemp=Tr-kelvin,LST=LST,Twi=Twi,dadd=dadd)
                    #print(TW)
                Outtemp.append(OT)
                Ambtemp.append(Ta)
                Cp, rho, vis, k, Pr, beta = Airprop(Tr) #room values
                if len(Time)<2:
                    T0 = TW
                    Tn1 = Tr
                    TSnew[0]=T0
                    TSnew.append(Tn1)
                    Q = 0
                    SUN = 0
                else:
                    TSold = TS[-1]
                    h1 = H
                    T0 = (h1*TSold[1]-wkdx*TSold[2])/(h1-wkdx)
                    #print(TSold[-2],Tr)
```

```
                    h2, LT = hccalc(Pr,g,beta,TSold[-2],Tr,vis,wl,k)
                    #print("h2=",h2,"LT=",LT)
                    Tn1 = TSold[-3]-(h2/wkdx)*(TSold[-2]-Tr)
                    #Then start heat transfering
                    if IR >0 :###DAYLIGHT HOURS CONDITION
                        SUN = 1
                    else: SUN = 0
                    TSnew, diff = Wallheat(TS,TW,Tr,SUN,dt)
                    variance.append(diff)
                    #then append
                    TSnew[0]=T0
                    TSnew[-1]=Tn1
                    Q = h2*Ac*(TSnew[-2]-Tr)
                #HO = 0
                if SUN:
                    Qtot = Q + HO
                    Heatout.append(HO)
                else:
                    Qtot = Q
                    Heatout.append(0)
                #if t % 4 == 1:print(Qtot) #print every 4th
                if SUN: TSnew[1]=TW
                TSnew = np.array([TSnew])
                TS = np.r_[TS,TSnew]
                deltaroom = 60**2*(Qtot-(Tr-Ta)/Rr)/MCp
                Tr = Troom[-1]+deltaroom
                Troom.append(Tr)
                Irrad.append(IR)
                SUNlist.append(SUN)
                #print("TS=",TS)
                t = t+1
                Time.append(t)
                Hs.append(H)
                #print("T=",t,",H=",H)
                if t > 3*24:break#notimes: break
            Troom[:] = [x-kelvin for x in Troom]
            Ambtemp[:] = [x-kelvin for x in Ambtemp]

            #IMPUT h2 calculator
            #Calculate new Tr
            #Wallheat()##




    from mpl_toolkits.axes_grid1 import host_subplot
    import mpl_toolkits.axisartist as AA
    import matplotlib.pyplot as plt

    if 1:
        host = host_subplot(111, axes_class=AA.Axes)
        plt.subplots_adjust(right=0.75,bottom=0.2)

        par1 = host.twinx()
        par2 = host.twinx()
        par3 = host.twinx()

        offset = 60
    #    new_fixed_axis = par2.get_grid_helper().new_fixed_axis
    #    par3.axis["right"] = new_fixed_axis(loc="right",
    #                                        axes=par2,
    #                                        offset=(offset, 0))
        offset = 120
    #    new_fixed_axis = par3.get_grid_helper().new_fixed_axis
    #    par2.axis["right"] = par2.axis["right"]#new_fixed_axis(loc="right",
                                           #axes=par2,
                                           #offset=(offset, 0))
```

```
    #    par2.axis["right"].toggle(all=True)

    #    host.set_xlim(0, 2)
        host.set_ylim(0, 2500)
        par1.set_ylim(4, 22)
        par2.set_ylim(-0.01, 1.01)

        host.set_xlabel("Time (Hours)")
        host.set_ylabel("Heatout (W)")
        par1.set_ylabel("Temperature (°C)")
        par3.set_yticklabels([])#("SUN 1=UP, 0=DOWN")

        p1, = host.plot(Time,Heatout, label="Heatout W")
        p3, = par2.plot(Time,SUNlist,ls='-',color='k', label="SUN")
        p2, = par1.plot(Time,Troom,ls='-',color='r', label="Roomtemp")
        p2, = par1.plot(Time,Ambtemp,ls='--',color='r', label="Ambient Temperature")

    #    par1.set_ylim(0, 4)
    #    par2.set_ylim(1, 65)

        host.legend(loc='upper center', bbox_to_anchor=(0.5,-0.1),
              ncol=3, fancybox=True, shadow=True)
        #host.legend(loc=4)

        host.axis["left"].label.set_color(p1.get_color())
        par1.axis["right"].label.set_color(p2.get_color())
        par2.set_yticklabels([])
        par2.set_yticks([])
        #par2.axis["right"].yticks([])

        plt.draw()
        plt.show()

        #plt.savefig("Test")


        MAX = 0
        MIN = 1000
        for i in range(24,len(Troom)):
            DIFF = abs(Troom[i]-TroomB[i])
            #print(DIFF)
            if DIFF>MAX: MAX = DIFF
            if DIFF<MIN: MIN = DIFF

    print("end")
```